



# **NAVAL POSTGRADUATE SCHOOL**

**MONTEREY, CALIFORNIA**

## **THESIS**

### **INTEGRATING STAKEHOLDER REQUIREMENTS ACROSS GENERATIONS OF TECHNOLOGY**

by

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September 2006

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<b>REPORT DOCUMENTATION PAGE</b>		<i>Form Approved OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
<b>1. AGENCY USE ONLY (Leave blank)</b>	<b>2. REPORT DATE</b> September 2006	<b>3. REPORT TYPE AND DATES COVERED</b> Master's Thesis	
<b>4. TITLE AND SUBTITLE:</b> Integrating Stakeholder Requirements Across Generations of Technology		<b>5. FUNDING NUMBERS</b>	
<b>6. AUTHOR(S)</b> Michael Robert Perz			
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Naval Postgraduate School Monterey, CA 93943-5000		<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>	
<b>9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> N/A		<b>10. SPONSORING/MONITORING AGENCY REPORT NUMBER</b>	
<b>11. SUPPLEMENTARY NOTES</b> The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
<b>12a. DISTRIBUTION / AVAILABILITY STATEMENT</b> Approved for public release; distribution is unlimited		<b>12b. DISTRIBUTION CODE</b>	
<b>13. ABSTRACT (maximum 200 words)</b>  Complex defense acquisition programs like that for the GPS have many requirements engineering challenges to overcome in order to deliver capabilities to customers and satisfy other stakeholders. To meet these challenges and stay within cost and schedule constraints, engineers and managers need system requirements information organized in a clear, complete, and efficient manner to support decision making. An effective methodology tailored to the needs of the program decision makers will ensure that important information is correct, organized, and readily accessible. The GPS program is implementing a methodology that includes standardized processes across its segments. However, the GPS program refrained from implementing a better requirements engineering approach and using its current requirements engineering tool to take advantage of this approach.			
<b>14. SUBJECT TERMS</b> requirements engineering, requirements development, requirements management, validation, verification, Dynamic Object-Oriented Requirements System, Global Positioning System, capabilities development document, specification, interface control document			<b>15. NUMBER OF PAGES</b> 115
			<b>16. PRICE CODE</b>
<b>17. SECURITY CLASSIFICATION OF REPORT</b> Unclassified	<b>18. SECURITY CLASSIFICATION OF THIS PAGE</b> Unclassified	<b>19. SECURITY CLASSIFICATION OF ABSTRACT</b> Unclassified	<b>20. LIMITATION OF ABSTRACT</b> UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)  
Prescribed by ANSI Std. Z39-18

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**INTEGRATING STAKEHOLDER REQUIREMENTS  
ACROSS GENERATIONS OF TECHNOLOGY**

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Submitted in partial fulfillment of the  
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**MASTER OF SCIENCE IN SYSTEMS ENGINEERING**

from the

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## **ABSTRACT**

Complex defense acquisition programs, such as the Global Positioning System program, have many requirements engineering challenges to overcome in order to deliver capabilities to customers and satisfy other stakeholders. To meet these challenges and stay within cost and schedule constraints, engineers and managers need system requirements information organized in a clear, complete, and efficient manner to support decision making. An effective methodology tailored to the needs of the program decision makers will ensure that important information is correct, organized, and readily accessible. The GPS program is implementing a methodology that includes standardized processes across its segments. However, the GPS program refrained from implementing a better requirements engineering approach and using its current requirements engineering tool to take advantage of this approach.

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## **ACKNOWLEDGMENTS**

I appreciate the contributions of so many people to this effort, but I extend my greatest appreciation to my thesis advisor and my second reader:

- Dr. Orin Marvel of the Naval Postgraduate School inspires me to become a better systems engineer with his no-nonsense style and sense of duty to his customers and stakeholders. Dr. Marvel volunteered to help me with my topic. I appreciate how he forces me to think critically.
- Dr. John Berg of the Aerospace Corporation inspires me to learn more about the GPS with his tremendous breadth of knowledge and experience. I appreciate how Dr. Berg agreed to help me determine and develop my area of research. He has been a pleasure to work with in my four years with the GPS program.

I also thank the following people for their enthusiastic contributions to this effort, and apologize to anyone I may have inadvertently missed: Pat Alexander, Tim Ator, LtCol Wayne Bell, Jack Campbell, Eric Clark, Major Jay Cryderman, Capt Mike Ewer, Randy Hutchings, Nita Maniego, Wally Owen, John Pezan, Mark Rhoades, Terry Roberts, Pam Silva, Capt Gerald Stewart, and Mike Turner.

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# **I. INTRODUCTION**

## **A. BACKGROUND**

With the Global Positioning System (GPS) program as an example, this research pursued the discovery of efficient and thorough methods for integrating system requirements across generations of system deliverables that incorporate new technologies and capabilities. Known as the Navstar GPS Joint Program Office until it was renamed in August 2006, the GPS Wing is the United States Air Force (USAF) system program office responsible for planning and acquiring deliverables that provide new GPS-based capabilities. Current practices expose the GPS program to the risk that technical incompatibilities will result across different blocks or generations of subsystems and their hardware and software interfaces. The reason for this is that not all relevant information is recognized and controlled by a central authority through a single, formal methodology. This research identified a more effective methodology for tracking the impact of every change or proposed change made to the GPS technical baseline. The GPS Wing could implement this approach with its existing requirements engineering tool, Telelogic AB's DOORS 7.1 database, and provide better decision-making support to GPS Wing leaders as a result.

The pursuit and recognition of valuable and timely information is a quest that persists for decision makers. Having ready access to knowledge of decision impacts across system segments and their successive deliverables would allow program decision makers to balance various and often competing system program objectives confidently. The outcome of this research recommends and demonstrates a requirements engineering methodology that helps systems engineers to answer the research questions posed below. When implemented fully, the GPS program's systems engineers should be able to take advantage of this methodology to perform quick and comprehensive technical analyses that support recommendations to the GPS Wing Commander. The GPS Wing Commander serves as the GPS System Program Director (SPD).

## **B. PURPOSE**

The greater purpose of this research effort was to offer requirements engineering improvements within the GPS program that systems engineers outside of the GPS Wing could apply for the benefit of their own acquisition programs. Programs that could benefit include other space programs that are held in the Space and Missile Systems Center (SMC) portfolio of acquisition programs at Los Angeles Air Force Base. (SMC funded the author's participation in the degree program for which this thesis satisfies a graduation requirement.) Ultimately, this research effort establishes an appropriate requirements engineering methodology for the GPS program and contributes to the set of best practices that help systems engineers and program managers for any complex system improve the level of cost, schedule, and technical success of their respective programs.

## **C. RESEARCH QUESTIONS**

The following research questions describe the extent of discussions that involved this author and other members of the GPS Wing at the onset of this research effort. This paper addresses all of these questions.

1. If the GPS program makes a decision to change a number in one place in the requirements or specifications, how does the program track and assess the impacts or ripples across system segments and capabilities? This question includes the following facets:
  - a. Requirements traceability
  - b. Requirements effectivities
  - c. Offline tools
  - d. Varying classification levels
  - e. Contracts

2. What does the current requirements engineering technology, DOORS, do well for the GPS program and what does it fail to do well or at all for the program?
3. In what ways are requirements documented?
4. What should the GPS program do about requirements that it anticipates and will affect other subsystem or segment deliverables, but do not exist yet?

For example, there will be a requirement to monitor the newest GPS signals. One satellite that can broadcast the M-Code signal is in orbit already, but it will be years before the GPS has a monitoring capability to support future GPS users of this type of signal.

5. What are the appropriate roles and relationships of the Capabilities Development Document (CDD), specifications, and Interface Control Documents (ICDs)?
  - a. For example, is the word *shall* in ICDs appropriate or, rather than provide direction, should ICDs simply describe interfaces?
  - b. How are ICDs handled in contracts when compared to other documents?
6. How should the program state requirements when perspectives differ across subsystems and segments?
7. What are the characteristics of a “good” requirement?
8. How can the program capture the rationale behind a requirement? It can be important to know whether a requirement exists because it is achievable or because of analysis.
9. How do a vendor and client verify that a particular requirement has been satisfied?
10. Who are the GPS program’s customers and other stakeholders?

Figure 1 below shows one way to organize these questions to see how they relate to each other in the context of system requirements engineering. There are four categories into which these research questions fit, and these are summarized as the following general questions:

- Where do requirements come from?
- How do we state requirements effectively?
- How should we document requirements?
- How should a program handle requirements changes?

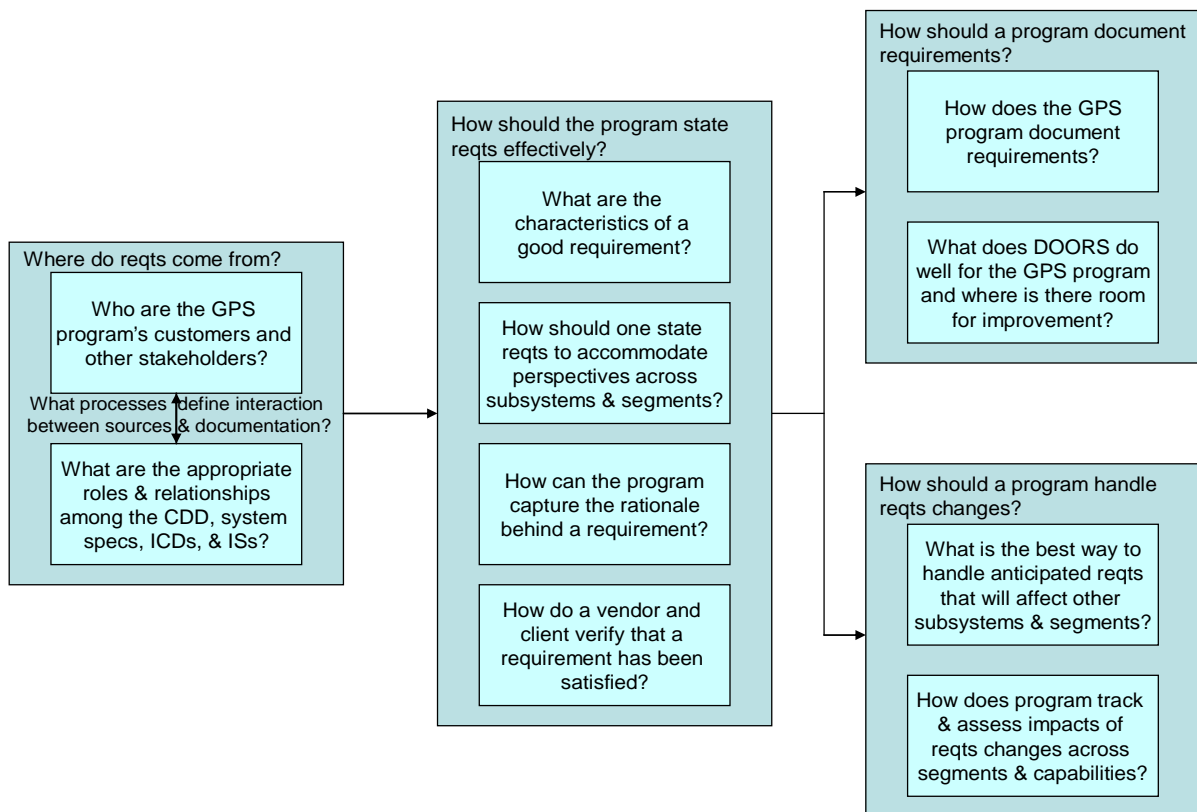


Figure 1. Relationship of Research Questions to Requirements Issues

#### **D. BENEFITS OF STUDY**

##### **1. Disciplined and Comprehensive Requirements Engineering Methodology**

A methodology can assist with analyzing the impacts of the factors and influences that contribute to the requirements engineering challenge. A methodology consists of three main components: techniques, models, and tools. Satzinger, Jackson, and Burd help to define this whole and its components, which are paraphrased as follows:

- a. Methodology** = guidelines for completing activities in a system development life cycle that include models, tools, and techniques
- b. Model** = a representation or abstraction of something real
- c. Tool** = something that helps with the creation of models or some other means to support a project
- d. Technique** = guidelines such as step-by-step instructions or general advice for completing an activity/task

(After Satzinger, Jackson, & Burd, 2004)

##### **2. Improved Decision Support Resources for Program Managers and Systems Engineers**

The GPS program faces many complex programmatic, technical, and political challenges. Effective documentation, analysis, management, and reporting tools for system requirements help program managers and systems engineers understand the impacts of decision alternatives and ensure that they make informed decisions. As this research revealed, the GPS Wing uses the DOORS tool without taking advantage of its most powerful features. Used with a more effective requirements-centric model, the DOORS tool can help decision makers improve the speed and quality of these decisions that affect the evolution of the GPS.

## **E. SCOPE AND METHODOLOGY**

### **1. Thesis Scope**

The thesis focuses on improving the models, tools, and techniques that support GPS requirements engineering from the elicitation of well-defined requirements from customers through the integration and test of deliverables. The requirements engineering recommended improvements can ensure that deliverables as designed and produced will satisfy well-defined requirements. This thesis addresses current shortfalls and concerns identified above in the research questions. In particular, the research findings include a better method for ensuring that potential impacts of new or modified requirements are easy to trace quickly. These improvements would benefit affected stakeholders who could then analyze the impacts and help program leaders make balanced decisions.

### **2. Approach/Methodology**

This section summarizes the activities that contributed to the research results and conclusions for this paper:

- a. A literature review of requirements engineering best practices and GPS requirements
  - b. Interviews of GPS program key personnel to uncover shortcomings in integrating requirements effectively
  - c. Identification of current GPS requirements engineering issues
  - d. Establishment of a DOORS account and receiving DOORS training
  - e. A review of how requirements from various relevant documents are currently handled in DOORS or by other means
- system specifications and derived documents



- Interface Control Documents (ICDs) and Interface Specifications (ISs)
  - the Capabilities Development Document (CDD) and its predecessor documents,
  - requirements documents classified at various levels
- f. Identification of examples of how processes and resources could be used to track requirements more effectively in order to facilitate better and faster requirements engineering decisions

## **F. ORGANIZATION OF THESIS**

Chapter I provides an introduction to the GPS Wing's requirements engineering challenges. In Chapter II, this paper introduces the GPS acquisition program and its stakeholders. Chapter II addresses the research question regarding where requirements come from and also describes the requirements management process. After explaining how the GPS Wing currently documents requirements, Chapters III and IV discuss the remaining three categories of research questions from Figure 1 above. While Chapter III focuses on an explanation of the contents within the literature reviewed, Chapter IV focuses on the application of the knowledge gained from both the literature reviewed and interviews granted by GPS Wing personnel. Chapter V provides a summary of recommendations and proposes areas for conducting additional research.

## **II. THE GLOBAL POSITIONING SYSTEM (GPS) ACQUISITION PROGRAM AND STAKEHOLDERS**

### **A. THE GLOBAL POSITIONING SYSTEM (GPS)**

The GPS is a space-based precision position, velocity, and timing (PVT) system conceived as a U.S. joint civil-military system led and staffed by the United States Air Force with participation by a variety of other U.S. government agencies and foreign military representatives. Other terms that describe GPS appropriately are *Global Navigation Satellite System (GNSS)* and *Radio Navigation Satellite Service (RNSS)*, because the coverage provided by the GPS is global and it transmits radio frequency signals on L-band carrier frequencies (from 1 GHz to 2 GHz according to IEEE standards) to the GPS users. GPS's L1 and L2 center frequencies are 1.57542 GHz and 1.22760 GHz, respectively. Figure 2 below depicts the segment components of the GPS and may serve as a helpful visual reference for the more detailed explanation that follows.

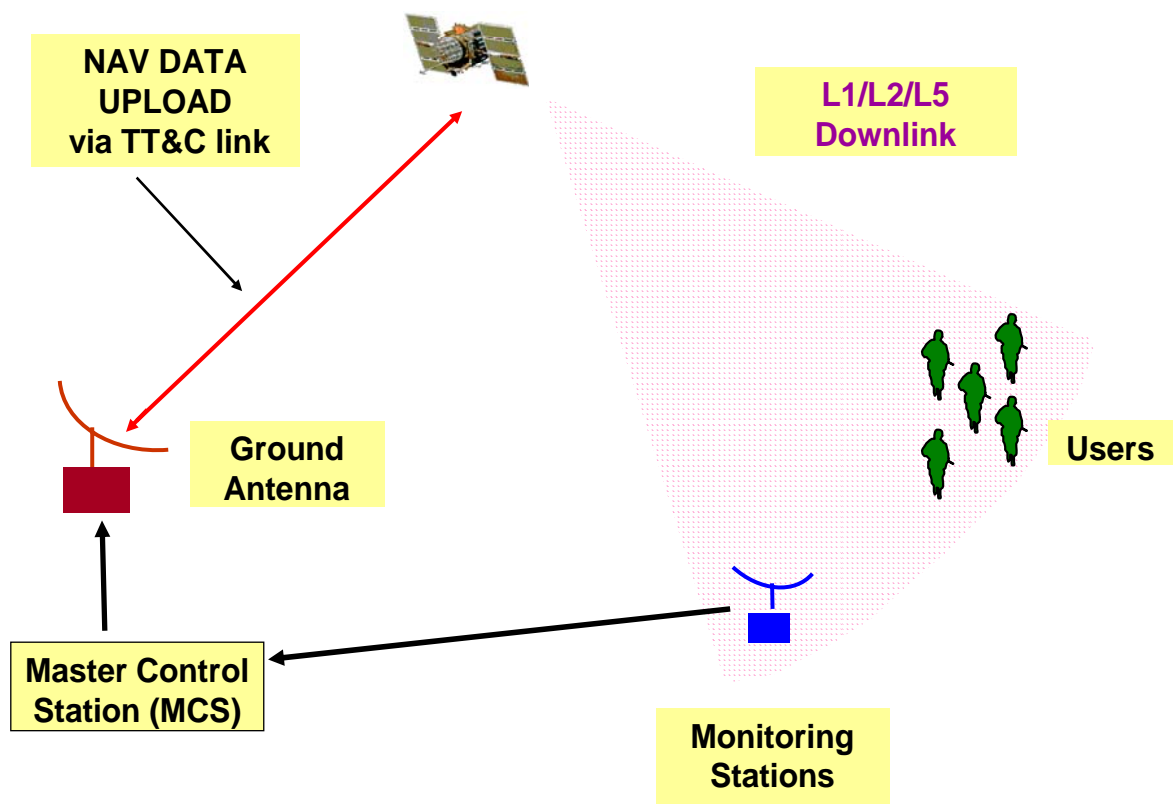


Figure 2. General depiction of the Global Positioning System segments (After Kaplan, 2006)

The space, ground (or control), and user segments represent the critical components of the GPS architecture. From the master control station (MCS) or its alternate facility, satellite operator personnel command and control the constellation of satellites that broadcast signals to monitoring stations (to create a feedback loop) and to GPS users. Users fall into two general categories: civil or military. Civil users benefit from the Standard Positioning Service (SPS) enabled by the coarse/acquisition (C/A) code signals broadcast by GPS satellites at the L1 frequency. Military users also have access to the encrypted Precise Positioning Service (PPS) that is based on the encrypted signal known as P(Y)

code, and this signal is broadcast at the L1 and L2 frequencies. If the SPS is not augmented by a regional ground-based or space-based differential GPS system, the PPS will provide more accurate results than the SPS. The National Security Agency (NSA) supports the cryptography needs of the GPS program.

GPS receivers on or above the surfaces of the earth receive signals that are broadcast from multiple GPS satellites to derive accurate ranging information with respect to each satellite and calculate unique PVT information for each user in real time. These signals are a combination of carrier frequency at which the GPS receivers receive the signals, a navigation message, and a ranging code. A GPS satellite's unique ranging code enables receivers—with their satellite constellation almanacs—to distinguish among the satellites in order to determine which satellites are “in view.” The use of these unique codes is necessary, because unlike radio stations that each use different frequencies to broadcast their content, the GPS signals from each satellite use the same carrier frequencies for the same purposes. The information regarding ranges to particular in-view satellites allows receivers to calculate their PVT information. More satellite signals available to a receiver typically result in better calculated solutions, but the relative positions of the satellites (the geometry) influence the accuracy of the calculations also. A minimum of four uncorrupted or “healthy” satellite signals are necessary for accurate position information. The reason that four satellites are needed instead of only three is that the ranging equations that describe the distance each signal travels from each satellite to a receiver include the 3-dimensional coordinates for the in-view satellites, the coordinates for the receiver, and the receiver's clock bias with respect to the satellites clocks. In general algebraic terms, the receiver would need four equations (one for each of four ranging signals) in order to solve for the four unknowns: the user's x, y, and z coordinates and receiver clock bias. Not taking into account the clock bias in a receiver can result in position errors of several hundred meters even with the most advantageous relative positions of only three satellites to each other and the user. Knowing deviations from expected satellite ephemerides also improves

the accuracy of receiver-calculated positions. Ample technical sources provide more detail about general GPS receiver technology. As of 2006 and in unobstructed settings, receivers can typically track eight or more GPS satellites than are needed to provide accurate results to users (Kaplan & Hegarty, 2006).

Satellite operators who work at the Master Control Station command and control the satellites of the GPS constellation. The operators ensure that the control segment performs the following functions defined by Misra and Enge:

- to monitor satellite orbits
- to monitor and maintain satellite health
- to maintain GPS Time
- to predict satellite ephemerides and clock parameters
- to update satellite navigation messages
- to command small maneuvers of satellites to maintain orbit, and relocations to compensate for failures, as needed

(Misra & Enge, 2001)

Some of the functions above relate to the new navigation messages the operators create and transmit to satellites in order maintain the GPS performance. Operators predict ephemerides and clock parameters using data obtained from the monitoring stations dispersed around the globe, and provide these predictions in the navigation message that is uploaded at least one each day to each satellite via ground antennas. Deviations from expected satellite orbits (or ephemerides) occur as a result of astronomical phenomena such as solar pressure and because the operators' gravity model is not perfect. The result of clock predictions is a definition of GPS Time and an effective synchronization of GPS satellite atomic clocks. These clocks are subject to very small errors that are still large enough to cause significant errors (several hundreds of meters in position) in receiver position calculations. GPS clocks use either cesium or rubidium frequency standards that are among the most stable

and precise clocks in existence. With the clock and ephemerides error information broadcast via the navigation message to and then from satellites, users' receivers can reduce the amount of error in their calculated PVT solutions. As the amount of time increases from the last update to the navigation message, the magnitude of PVT errors increases with the increasingly older satellite clock and ephemerides parameters.

The orbits for the GPS constellation include 24 primary orbital slots—one for each satellite and four in each of six orbital planes to provide nearly even coverage around the globe. For several years, there have been surplus satellites distributed (not necessarily evenly) across the planes of the constellation and contributing to the quality of the PVT information provided to users. Older satellites that are closer to failure tend to be placed near other such satellites either in the same plane or in adjacent planes to ensure robust coverage around the globe. Constellation management decisions like these involve analysis of the most likely failure scenarios and their impacts. An AFSPC-wide community meets quarterly to make decisions that sustain the GPS constellation and minimize the service degradation in terms of duration and geographic footprint on any given day. This body takes into account the health risks forecasted for each satellite and each plane of satellites. Because each operational satellite makes an impact on system performance, decisions that contribute to this robustness often involve combining decisions to choose orbital destinations for new satellites and to reposition satellites currently in the constellation. Ultimately, this body shares the GPS stakeholders' number one priority to sustain the GPS service at a high level of quality.

## **B. THE GLOBAL POSITIONING SYSTEM (GPS) WING**

### **1. Organization**

The GPS Wing is a program office responsible for the acquisition and evolution of the GPS. Several program office Divisions, Groups, and support

contractors support the Wing Commander in his role as System Program Director (SPD). These organizations fall into five general categories shown in Figure 3:

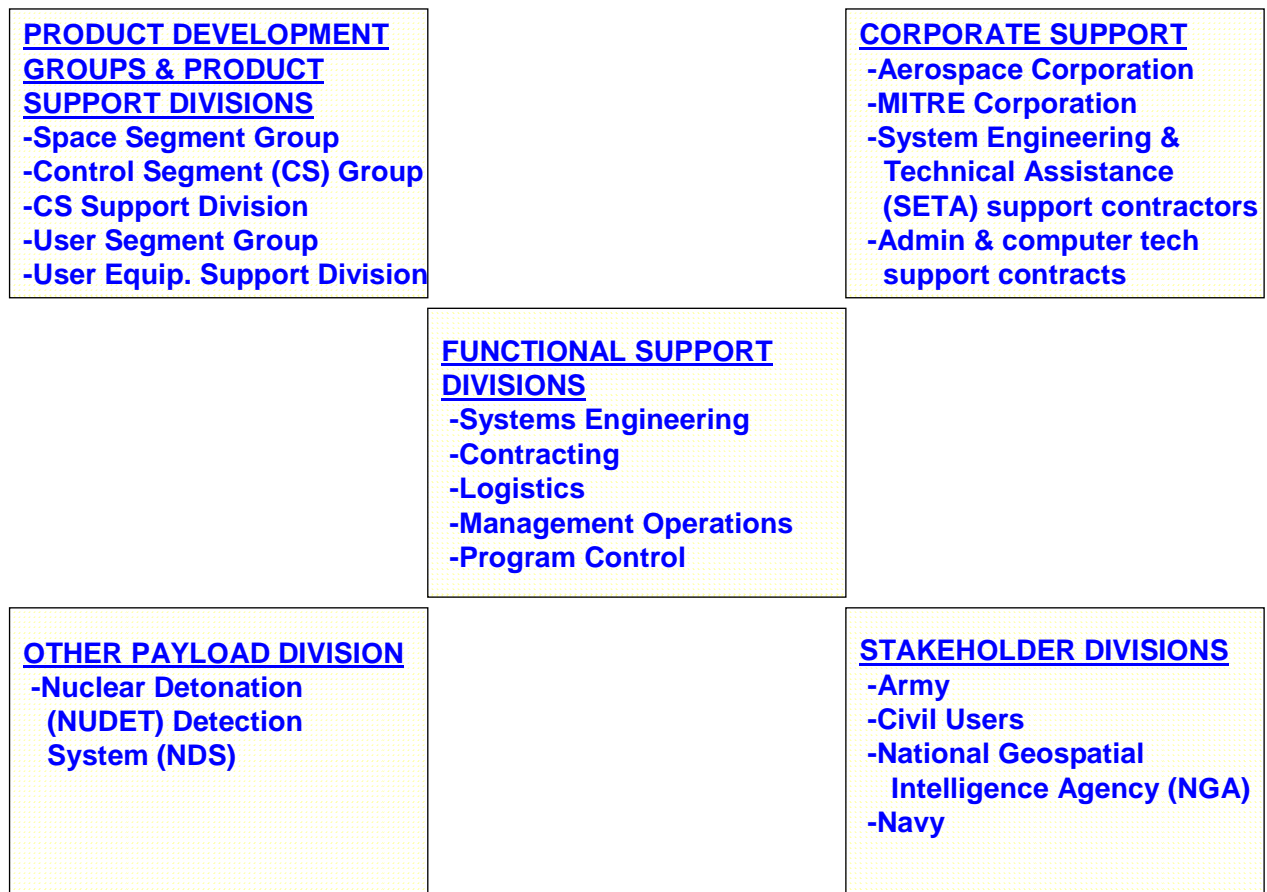


Figure 3. GPS Wing's Division, Group, and Corporate support for the SPD

## 2. Roles and Responsibilities

### a. *Product Development and Product Support*

The GPS Wing has a product development Group for each of the three GPS segments: ground (or control), space, and user. They each manage their own development contracts, and work with the System Engineering and Logistics Divisions to ensure compatibility of requirements, effective integration,

test, delivery, and user acceptance of new system components. The Contracting and Program Control Divisions also support the changing needs of these acquisition efforts.

The Space Segment Group is responsible for the acquisition of the space vehicles. Current acquisition efforts include the Block IIR-M satellites, some of which remain to be launched, the Block IIF satellites being manufactured, and the Block III variants for which the GPS Wing has not chosen a vendor.

The Control Segment Group is responsible for the upgrade of the current and acquisition of the new ground infrastructure necessary to command and control the space vehicles. This infrastructure includes master control stations (primary and backup), ground antennas, monitoring stations, other communications equipment (switches, routers, and transmission lines) to connect these modules, and the software necessary to integrate and operate this equipment. Software acquisition is a challenging part of the Control Segment modernization that has resulted in cost and schedule overruns. The Control Segment also uses the Air Force Satellite Control Network (AFSCN) Remote Tracking Stations (ARTS) to support testing and satellite orbital movement operations, and National Geospatial Intelligence Agency (NGA) monitoring stations to augment the GPS monitoring stations around the world.

The Control Segment Product Support organization in Colorado Springs, CO provides product maintenance and upgrade services requested by the operators. Upgrades can include changes to the user interface or additional functions.

The User Segment is responsible for the acquisition of GPS PPS receivers used by U.S. and allied foreign military services. Products acquired by this segment include the Precision Lightweight GPS Receiver (PLGR) handset and the Combat Survivor Evader Locator (CSEL) system. Current acquisition



programs include more advanced hand-held and platform-mountable receivers for navigation and precision targeting.

The User Equipment Support Division at Robbins Air Force Base, GA provides support for the GPS military receiver users. This support includes user training as well as equipment maintenance, troubleshooting, and upgrades.

***b. Corporate Support***

Like the other program offices at the SMC, the GPS Wing relies on the invaluable technical support provided by corporate partners. These include the The Aerospace Corporation, The MITRE Corporation, and System Engineering and Technical Assistance (SETA) contractors.

The Aerospace Corporation and The MITRE Corporation are both Federally-Funded Research and Development Corporations (FFRDCs) that receive funding from Congress and operate as non-profit corporations. This allows employees of both corporations to have the privilege of access to vendors' proprietary information when such access is necessary to support official government business. This information is usually technical in nature since most employees of these FFRDCs are engineers or their managers. This special status precludes these FFRDCs from competing against vendors who do operate for profit. Aerospace has its headquarters adjacent to Los Angeles Air Force Base in El Segundo, CA and has the larger presence of the two firms. MITRE has its headquarters in Bedford, MA and an office in El Segundo, CA.

Apart from the FFRDCs, for-profit contractors compete for SETA contracts to support the GPS Wing's technical needs. Employees of these firms support the GPS Wing in a manner similar to that of the FFRDCs. At the time of this research effort, these firms included ARINC Engineering Services, LLC of El Segundo as prime contractor; Science Applications International Corporation (SAIC); Tecolote Research, Inc.; Overlook Systems Technologies, Inc.; and

Teledyne Brown Engineering, Inc. Different firms support administrative and information technology needs through other contracts.

***c. Functional Support Divisions***

The functional support divisions along with their assigned corporate supporter team members serve to accommodate and balance the needs of the product development groups and product support organizations, represented stakeholders, and the NDS program.

The GPS Wing's Systems Engineering Division guides the analysis and design of the GPS system architecture and capabilities. This work includes defining and coordinating requirements documents that include the Capability Development Documents (CDDs), system and segment specifications, interface control documents (ICDs), Interface Specifications (ISs), and other technical guidance necessary to meet operator and user needs. Vendors use this guidance to design their subsystems and validate the performance of these designs. All stakeholders voice their input to ensure that program decisions accommodate their needs. The Chief Engineer and ultimately the Wing Commander balance these needs based on the guidance and direction from the DoD, regulatory bodies, and the needs of the GPS stakeholders. Section D1 explains the division of responsibilities within the Systems Engineering Division.

The Chief Engineer, Group Commanders and Wing Commander cannot make informed decisions without consulting with the GPS Wing's Program Control Division. This division has financial and cost analyses branches to help ensure that the program only takes actions that the Wing's budget will allow. While the Systems Engineering Division focuses on technical baselines and the Program Control Division focuses more on cost and schedule baselines, both divisions must work together with the product development groups to balance cost, schedule, and technical needs of the GPS Wing's acquisition programs. The Program Control Division also serves as the focal point for external (DoD) requests for analysis.

By negotiating contracts with vendors, the GPS Wing's Contracts Division works with the product development groups to ensure that these firms will design and build GPS subsystems in accordance with the compliance documentation included on the respective contracts. The Contracts Division manages several development contracts and oversees the bidding for others like the separate Space and Control Segments' Block III contracts. Control over these contracts is important for ensuring that the multiple prime contractors deliver GPS subsystems that will work properly with the other vendors' deliverables.

The GPS Wing's Logistics Division works with AFSPC to meet the integrated logistics support (ILS) needs of the GPS program. Capt M. Ewer of the Logistics Division (personal communication, July 10, 2006) describes the division of responsibilities as they are summarized in Table 1 below:

GPS Wing-Level Lead	AFSPC-Level Lead
<ul style="list-style-type: none"> <li>• Maintenance planning</li> <li>• Supply support</li> <li>• Training &amp; training support</li> <li>• Technical data</li> <li>• Packaging, Handling, Storage, and Transportation (PHS&amp;T)</li> <li>• Design interface</li> </ul>	<ul style="list-style-type: none"> <li>• Support and Test Equipment/Equipment support</li> <li>• Manpower and personnel</li> <li>• Computer Resources support</li> <li>• Facilities</li> </ul>

Table 1. ILS elements allocated among GPS Wing and AFSPC levels.

The GPS Wing's Management Operations Division provides office support functions to meet the personnel and office needs for all GPS Wing employees.

**d. Other Payloads**

The non-PVT payload that the GPS program supports is the Nuclear Detonation (NUDET) Detection System, or NDS. The DoD decided to add this payload to the GPS space vehicles in order to leverage the continuous global coverage that the GPS provides.

**e. Stakeholders**

As stakeholders in the evolution of the GPS, other government agencies have GPS Wing division-level offices to represent them within the GPS program. These entities include the other US military services, the National Geospatial Intelligence Agency, and civil users.

The Army's and Navy's concerns relate directly to the quality of PVT services provided to their respective members through their diverse GPS receiver equipment sets. There are many adaptations of GPS receivers to the needs and platforms of various military systems.

Known previously as the National Imagery and Mapping Agency (NIMA), the National Geospatial Intelligence Agency (NGA) provides the information necessary to relate GPS coordinates to the geographic features of the world. Modeling the geographic features of the earth is part of a discipline known as geodesy.

The civil users collectively include more people than military users, and the number of civil applications continues to expand. While these users include emergency responders, surveyors, members of the agriculture industry, athletes, and many others, the civil agency most interested in the evolution of the GPS is the United States Department of Transportation (DoT). Within the DoT, the Federal Aviation Administration (FAA) has a strong interest in understanding and influencing policy and technical decisions for the GPS in order to support the needs of civil aviation navigation and the Wide-Area Augmentation System

(WAAS). This system would include geosynchronous satellites to work with the GPS to improve GPS accuracy and availability to satisfy civil aviation navigation and safety requirements.

The satellite launch community participates in constellation management decisions because the GPS program must coordinate the timing of its launch plans with the launch pad schedule controlled by the launch community. Launches are planned several years in advance, and are subject to changes based on DoD and national needs.

### **3. GPS Program Requirements Challenges**

With the diverse sources of change to the system that include the functional support divisions, product development groups and product support organizations, and other stakeholders, there exists the risk that requirements generated or requirements changes made for one part of the program will have **unintended consequences** that are difficult to trace or accommodate. The Systems Engineering Division has the Herculean task of managing the complexity of the GPS program, and the tools used and frequent turnover common in military organizations are among the sources of confusion and risk for which a stricter approach to requirements engineering could help ensure more effective integration of the system's components across system segments. Every requirements integration/engineering activity should strengthen the program's ability to fulfill its mission and obligation to its stakeholders. These engineering impacts will not occur without contractual, cost, and/or schedule implications.

The GPS program faces engineering challenges, different rates of modernization progress across the three segments, and a tremendous amount of interest and use beyond the Department of Defense. With respect to the latest signals and associated services, Control Segment modernization lags behind Space Segment modernization, and both lag User Segment modernization. For several years, users have had GPS receivers that are capable of operating within

the improved GPS security architecture that the Control Segment will not be able to implement for at least two more years. While it is necessary to have satellites in orbit that can support the newest planned capabilities before they are implemented by the Control Segment, the Control Segment lags far enough in development that it cannot support requirements engineering work needed for the Space Segment to continue its own software development efforts. Also, influences outside of the Department of Defense further complicate plans to modernize GPS. These constraints include domestic and international laws and regulations, other U.S. government agencies' and commercial interests, and international agreements. Program managers and systems engineers must be aware of these constraints as they contend with the realities of the acquisition program baseline.

### **C. THE GPS ACQUISITION PROGRAM BASELINE (APB)**

#### **1. Overall**

The APB describes the delivery of GPS upgrades and capabilities:

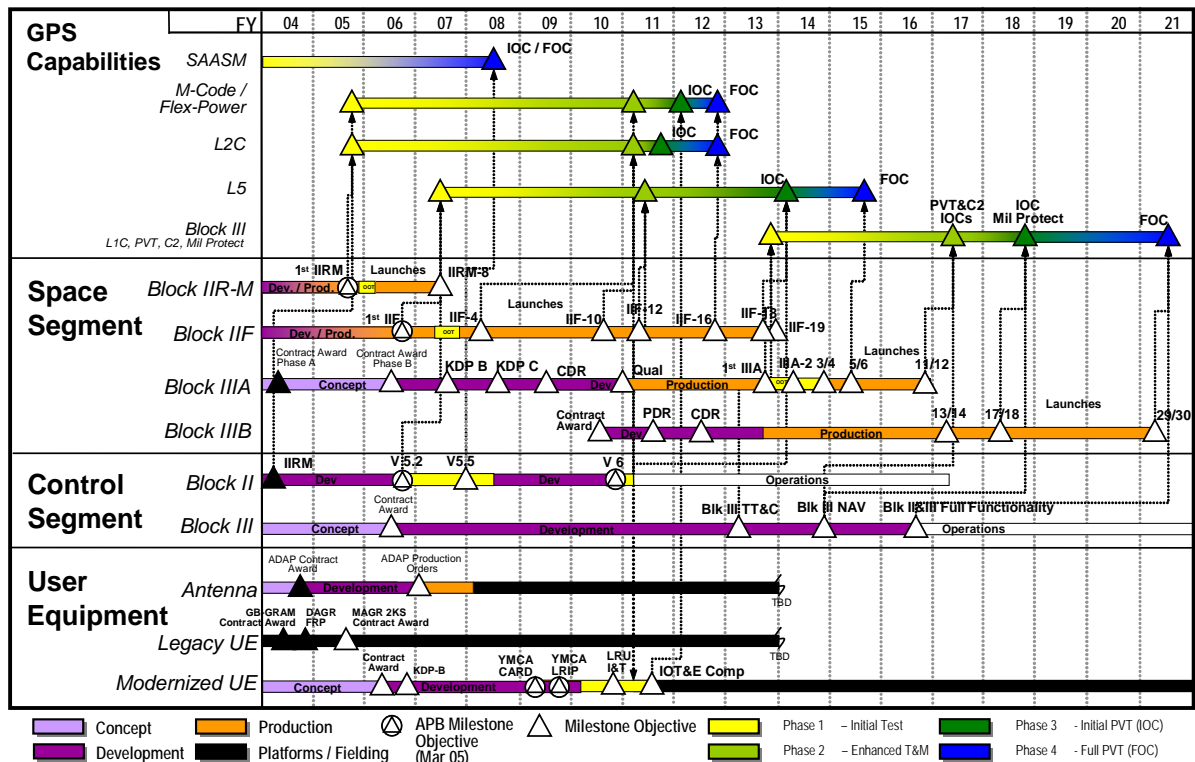


Figure 4. April 05 GPS Enterprise Schedule (D'Alessandro & Turner, 2006)

Figure 4 summarizes the timing of GPS modernization activities. The top portion of the figure lists the new capabilities that the GPS will provide over time, while the bottom three sections devote themselves to summarizing the modernization of the three GPS segments. It is through the modernization of these segments that the new features will become available to GPS users. Acronyms in Figure 4 are defined as follows:

- Phase 2 – Enhanced Timing and (Navigation) Messaging (T&M) refers to an improvement in both of these named capabilities

- Initial Operational Test and Evaluation (IOT&E) is a phase of system testing in an operational environment
- The Preliminary Design Review (PDR) is the forum for the appropriate program manager to determine whether or not “test and analytical evidence... prove that all performance numbers are achievable and no significant performance risk remains, and [whether or not] the end product will satisfy the customer” (Forsberg, Mooz, & Cotterman, 2000).
- The Critical Design Review (CDR) is the forum for the appropriate program manager to determine whether or not “tests and demonstrations... prove that building and coding to the proposed documentation is achievable with acceptable risk and, [whether or not] the end product will satisfy the customer” (Forsberg, Mooz, & Cotterman, 2000).
- Telemetry, Tracking, and Control (TT&C) is the name for the information provided by a communications bus.
  - *Telemetry* is any information transmitted from a remote location.
  - *Tracking* relates to information used to determine changes in satellite position.
  - The system operators *control* the satellites with messages provided via the TT&C communications bus.

## **2. New Capabilities**

New capabilities will include incremental security architecture advancements known as (Block IIF) SAASM and Block III Mil Protect. Newly-designed signals will also be broadcast at frequencies and power levels that conform to U.S. and international regulatory filings. Before any new capability becomes available, each segment modernization effort must achieve its own



milestones in order to support delivery of the capability. The difficulties in achieving these milestones are revealed below in the respective segment sections.

The second-generation security architecture and third-generation cryptography are known collectively as SAASM. This acronym is misleading because it represents more than the Selective Availability Anti-Spoof Modules in GPS receivers that have been available to the P(Y) code-based Precise Positioning Service (PPS) users for years. When supported by the Block IIF control segment, the capabilities linked to SAASM will improve cryptographic key distribution to PPS receivers (used mostly by military users) and reduce their susceptibility to spoofed GPS signals that can lead to significant PVT errors.

Block III advancements are expected to include another civil signal, controlled signal power generation, and another security architecture improvement. The Block III security architecture that will replace SAASM is known as Military Protect and will work with the M-Code-based PPS. The term *M-Code* is the accepted shorthand for the new Military Code ranging signal. Flex-power will be a capability to increase the GPS signal power to support military needs in chosen parts of the world. L1C will be new civil signal broadcast by the GPS Block III satellites.

L2C, L5, and L1C are the L-band civil signals listed in the order they will reach Initial Operating Capability (IOC) and Full Operating Capability (FOC). These signals are shown in the GPS Capabilities section of the GPS Enterprise Schedule in Figure 4. FOC for a type of signal requires 18 healthy satellites to broadcast it. Note that only users who have receivers capable of processing these new signals will benefit from the capabilities offered. The M-Code signal and Flex-Power feature will achieve IOC at the same time as the L2C signal. The reason for the expected simultaneous realization of these signals and capabilities is that these all depend on Block IIR-M satellites and the satellite variants that will follow. Refer to Figure 4 to see this type of connection between the GPS segment deliverables and capabilities.

### **3. Space Segment**

The remaining Block II generation of satellites that will provide new signals includes the Lockheed Martin Block IIR-M and the Boeing Block IIF satellites. The IIR-M vehicles can broadcast the L2C Civil Signal and the M-Code military signal. The Block IIF satellite will also broadcast the L5 civil signal, which is of particular interest to the DoT and FAA for civil aviation use.

The GPS Wing has not chosen the vendor that will design and build the Block III generation of satellites, but these satellites will add the L1C civil signal that the U.S. government expects will be a common signal among GPS, the European Union's planned Global Navigation Satellite System (GNSS) known as Galileo, and Japan's planned Quazi-Zenith Satellite System (QZSS) to augment the GPS over Japan.

Civil users currently have access to C/A code only, as other signals (L2C, L5, and L1C) are not yet available. These future signals will allow more modern GPS receivers to take advantage of these signals in order to improve the PVT solutions they calculate.

### **4. Control Segment**

Like the Space Segment, the Control Segment has Block II and Block III upgrades planned. These lag behind Space Segment modernization and are necessary in order to implement the capabilities designed and built into the satellite vehicles. Currently, the Block IIR-M satellites are capable of broadcasting signals that the Control Segment will not be able to support until Block III. The first Block IIF Control Segment delivery will replace the current system and provide an improved system architecture and system operator interface. The second delivery will add the SAASM capabilities described in section 2 of this chapter. After reductions in scope to the Block IIF Control Segment contract, this series of deliverables will serve largely as a stop-gap between the current Control Segment and the Block III Control Segment. In addition to enabling new SAASM capabilities, this block is essential for providing

the means to command and control the Block IIF satellites. The GPS Wing decided against upgrading the current system to support Block IIF satellites.

## **5. User Segment**

The User Segment is pursuing a variety of modernization efforts to ensure that military users have the ability to take advantage of the latest capabilities available to them. Beyond making the necessary technical documentation available, the GPS Wing does not support efforts to develop or produce civil user equipment. User Segment programs include development of entire receivers, as well as new hardware that the User Equipment Support Division can install in existing receiver equipment. New capabilities to users will result from the following list of active programs:

- Advanced Digital Antenna Panel (ADAP) for aircraft
- Ground-Based GPS Receiver Application Module (GB-GRAM) for a variety of U.S. Army platforms and munitions
- Defense Advanced GPS Receiver (DAGR) handsets
- Miniature Airborne GPS Receiver (MAGR) 2000S
- Modernized User Equipment (MUE)
  - the GPS Wing will not negotiate a contract to build MUE
  - the GPS Wing supports the development of the YMCA card to be used in MUE for receiving and processing the current military P-Code (known as P(Y)-Code when encrypted), the future military M-Code, and the coarse acquisition (C/A) code signals.

Current military GPS users have receivers that are capable of operating within the currently unavailable SAASM architecture.

## **D. CURRENT REQUIREMENTS ENGINEERING METHODOLOGY**

### **1. The GPS Wing Systems Engineering Division**

The Systems Engineering Division serves as the clearinghouse for balancing requirements needs across GPS Segments and stakeholders. In particular, the Chief Engineer relies on the Requirements Branch, Integration Branch, Engineering Projects Branch, and Security Engineering Branch to support requirements engineering needs. The Test Branch supports verification of GPS requirements.

The Integration Branch interacts with the product development teams within the Space, Control, and User Groups to resolve both requirements and design conflicts. The latter often results from differences in interpretation of the former by two or more development teams that must ensure effective interfaces between their deliverables. Because of the cross-segment interaction, the Integration Branch is well-positioned to manage most of the Interface Control Documents (ICDs) that govern the many GPS subsystem and stakeholder interfaces. However, there are instances where vendors that are responsible for developing a subsystem on one side of an interface also have control over the ICD. These vendors are called Interface Control Contractors (ICCs). This kind of arrangement causes conflicts because the vendor developing the subsystem on the other side of the same interface is left at a disadvantage when the ICC proposes ICD changes and implements them before the proposed changes are approved.

With the input of the GPS program's customers at AFSPC as well as other stakeholders, the Requirements Branch creates the Capability Development Document (CDD), the System Specifications, the Standard Positioning Service Performance Standards (SPS PS) and the Precise Positioning Service Performance Standards (PPS PS). Current and older versions of these documents apply to different segment development efforts, and the contracts that are relevant to those efforts. The other GPS stakeholders with whom the Requirements Branch interacts include the Aviation community's representatives

from the Federal Aviation Administration (FAA), the U.S. Department of Transportation (DoT), and the International Civil Aviation Organization (ICAO). The SPS PS document includes a publicly releasable subset of information that is available in the GPS System Specification, top-level system interface control document (ICD), and some lower-level specifications and ICDs.

The Engineering Projects Branch handles international and domestic regulatory issues that relate to the approval to broadcast signals in the manner approved by the appropriate regulatory bodies. The U.S. government files for rights to broadcast in pre-determined frequency bands and at negotiated power levels to ensure that other users of these and adjacent frequency bands suffer no harmful interference to their interests as a result of GPS operations. The U.S. Government must define the signals that the GPS broadcasts, and the Engineering Projects Branch handles the signal design of new signals to ensure that these signals meet GPS needs for supporting users and satisfying regulatory agreements.

Once part of the Engineering Projects Branch, the recently-formed Security Engineering Branch assumed responsibility for all GPS security architecture needs. These include such areas of concern as the cryptographic protection of military signals for use by only authorized users as well as other features not disclosed by the program for security reasons.

## **2. GPS Requirements Documents and Requirements Sources**

Figure 5 summarizes the diversity of requirements documentation that guides the definition and evolution of the GPS, and the stakeholder organizations that contribute to that documentation. With the exception of the Systems Engineering Division, the categories of stakeholders are grouped outside of the largest box in the figure that engulfs the names of the requirements documents.

User communities such as the membership of the North Atlantic Treaty Organization (NATO) with its Standardization Agreement (STANAG), the

classified High-Accuracy Navigation Users (HANU), and the United States Coast Guard (USCG) are among the users outside of the DoD who influence the system. The civil users who stand out include the domestic and international civil aviation organizations. There is frequent interaction between the Department of Transportation's (DoT's) Federal Aviation Administration (FAA) and the international body of which it is a member, the International Civil Aviation Organization (ICAO). This interaction influences documents such as the Standards and Recommended Practices (SARPs), the description of the Future Radio System (FRS), and the Standard Positioning Service Performance Standards (SPS PS).

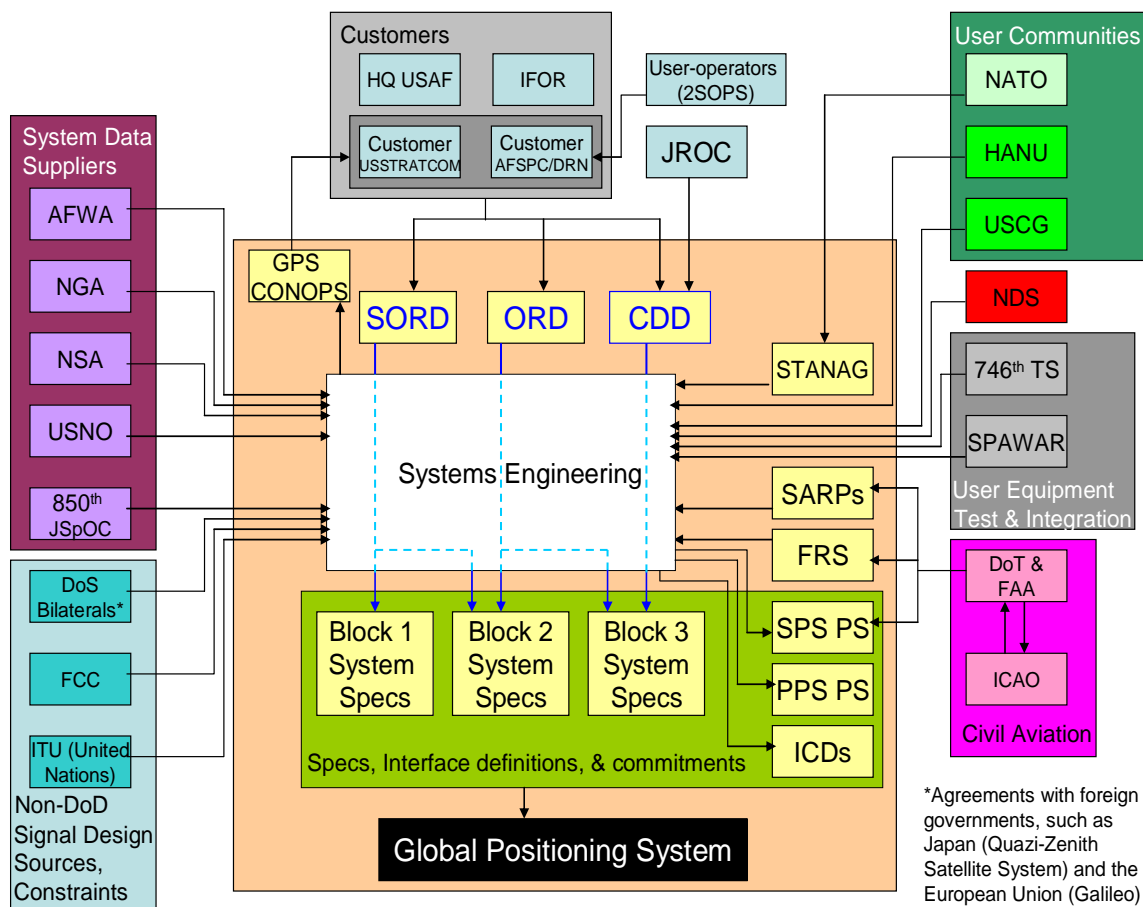


Figure 5. GPS Requirements Documents and Requirements Sources (After Alexander, 2006; and After Chief Engineer Navstar GPS Joint Program Office, 2006c)

Organizations that ensure that military users receive suitable receiver equipment include the 746<sup>th</sup> Test Squadron and the Space and Naval Warfare Systems Command (SPAWAR). Beyond testing, SPAWAR is responsible for acquiring and integrating GPS receiver equipment on Navy and Marine Corp sea and air platforms.

The customer paying for the GPS is the U.S. Air Force Space Command (AFSPC), which receives its funding from headquarters U.S. Air Force (HQ USAF). In turn, AFSPC's customer is the 50<sup>th</sup> Space Wing and its 2<sup>nd</sup> Space Operations Squadron known as 2SOPS. The Interagency Forum for Operational Requirements (IFOR) is a joint civil-military forum chaired by the AFSPC-level military and civil requirements representatives who ensure inclusion of civil requirements in GPS CDDs. USSTRATCOM is a cross-service organization that ensures it can provide direction to the operators of the GPS with Space Tasking Orders (STOs). These STO messages direct operators to include commands in the navigation message that change the behavior of the GPS in a theater of operations and benefit military users. The requirements levied by these organizations are now scrutinized by the Joint Requirements Oversight Council (JROC).

The GPS cannot exist as a useful system without the contributions of various organizations. These include the Air Force Weather Agency (AFWA), which tracks solar flares that affect the transmission of GPS signals. Also noteworthy are the National Geospatial Intelligence Agency (NGA) mentioned in section B2 above and the National Security Agency (NSA) mentioned in section A above. The United States Naval Observatory (USNO) provides another atomic-based time reference against which to compare GPS time. The 850<sup>th</sup> Joint Space Operations Center (JSpOC) has an interface with the GPS for receiving GPS data in a particular format.

Lastly, the GPS inherits technical requirements and constraints as a result of the regulatory environment and agreements reached between the U.S. and other nations. These regulations and agreements encompass a range of

concerns such as military interests, compatibility—the degree to which there is or is no harmful interference) between two radio frequency-based systems, and even the definition of signal characteristics for possible common use in other Radio Navigation Satellite Systems (RNSSs) that could work with GPS.

The GPS Wing considers all proposed requirements and changes with the requirements management process. This process requires a great deal of interaction among the different stakeholders represented within the GPS program. The next section describes this process.

### **3. The GPS Requirements Management Process**

The requirements management process requires that the Systems Engineering Division consider the technical implications of adopting or changing requirements. Because of schedule and cost impacts that can result to the programs' segment development contracts, this division cannot make decisions without coordinating with product development and functional groups. Figure 6 shows the internal program interaction that occurs before a decision to rebaseline the GPS program's requirements. This interaction is designed to work through the system's Configuration Control Board (CCB) to coordinate all requirements baseline changes. All affected stakeholders contribute to the decision made through the CCB.

The Systems Engineering Division performs much of the requirements analysis necessary to foster productive discussions about new requirements with the other stakeholders. This analysis includes eliciting, collecting, developing, and verifying customer and other stakeholder requirements before translating these into possible GPS segment development program requirements. The Engineering Review Board (ERB) is the forum for discussion within the Systems Engineering Division that occurs before forwarding proposed requirements (including changes) to a system CCB to involve the other program facets in the decision regarding whether and/or how best to implement a new requirement or



requirement change. The ERB rejects proposed changes to the program technical baseline if these proposals require more analysis before CCB consideration.

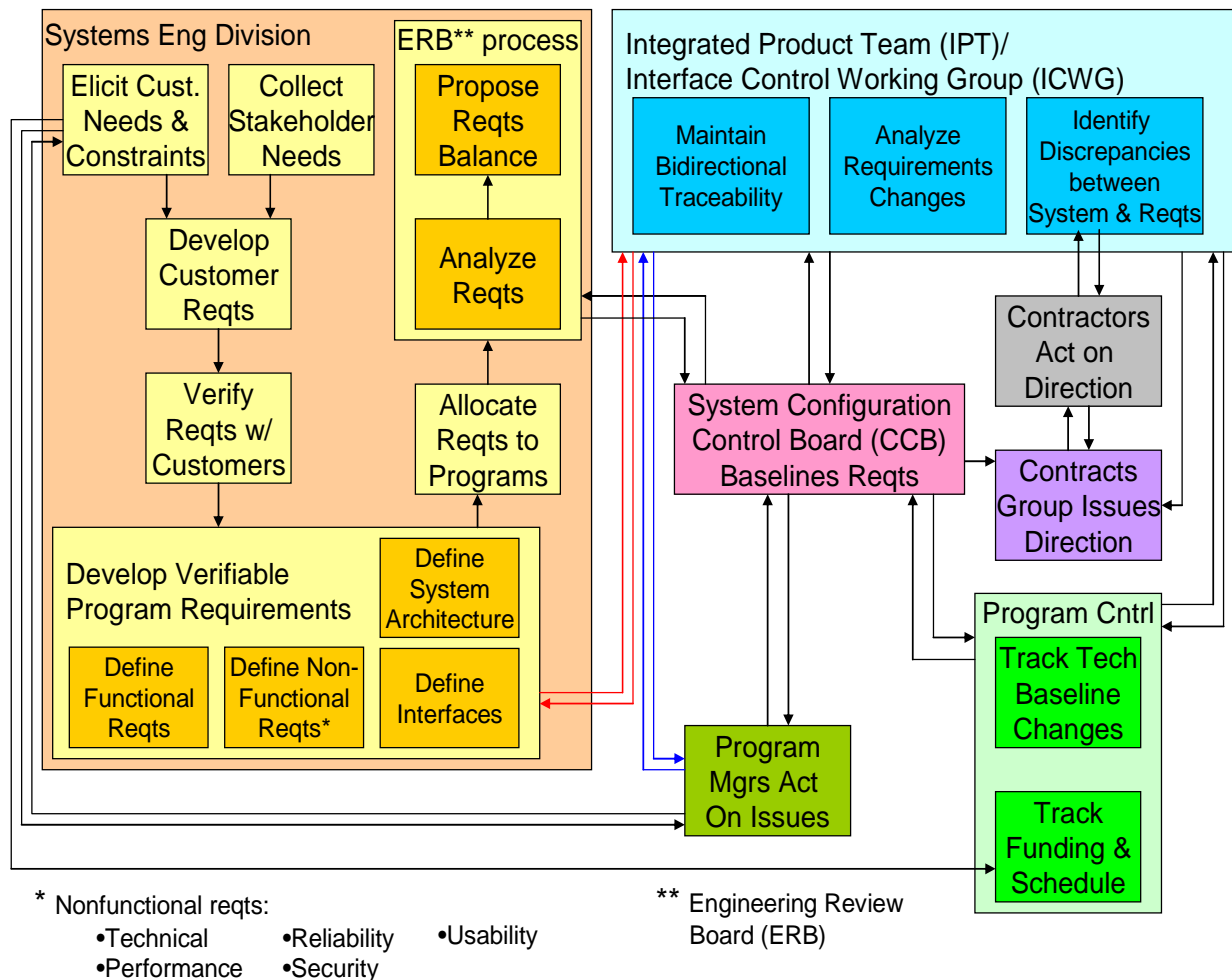


Figure 6. GPS Wing Requirements Management Process (After Chief Engineer Navstar GPS Joint Program Office, 2006a, 2006c)

Segment development programs will often propose changes to requirements for a few reasons. Not only does the GPS Wing have the ability to change requirements, but the vendors who control some of the interface definitions also have this ability. There may be technical challenges that are too

difficult or costly to overcome in the scheduled amount of time. Also, segment program requirements usually change through testing phases. Sometimes it is easier to change requirements than it is to satisfy them. This approach is beneficial when analysis reveals that the benefit of changing a requirement outweighs the cost. This can occur from a perspective of achieving a level of overall system performance, but may occur in the context of shifting the relative burden of satisfying a requirement from one segment to another. Vendors may propose such changes if in their own respective interests without regard for the best interests of the GPS program. If implemented, the vendor responsible for the other side of the interface would need to accommodate changes to interface requirement, and such an impact would have costs that the government would have to cover. More broadly, shifting any requirements via the CCB can have contractual impacts that the Contracts Division must provide as direction to the appropriate vendors to implement.

Direction to vendors is likely to have cost impacts on the development contracts, and all cost impacts require coordination with the Program Control Division. Not surprisingly, technical and schedule changes have impacts on contracts that obligate the program to cover any costs. Thus, the Program Control Division finds itself coordinating with the other GPS Wing's organizations to ensure that the program can meet proposed obligations before committing to requirements baseline changes that the Wing cannot implement within schedule and budget constraints. Segment development program managers help to assess the cost, schedule, and technical impacts to their respective programs as a result of proposed changes.

## **E. IDENTIFIED RISKS AND CONCERNS**

There are forces that affect the ability of the GPS Wing to execute its development programs. Customers, operators, and users expect programs to remain on schedule and deliver promised capabilities. On the other hand, ambitious and perhaps unrealistic schedules increase the risk of program failure.

Loosely written contracts during Acquisition Reform era of the mid-1990s also limit the government's ability to govern the execution of current contracts. As the GPS Wing tries to recover from the development problems of these programs, customers disregard past experience and continue to set high expectations for the Block III subsystem programs' cost, schedule, and technical successes.

### **1. Pressures from Customers, Operators, and Users**

As a joint military and international civil resource, the GPS attracts a tremendous amount of interest. It is a high-value and complex system that has provided PVT information for nearly two decades, and yet it is also under continuous development. Unfortunately, development has proceeded unevenly across GPS Segments. As the Block III satellite development proceeds, the lag in Control Segment development may continue due to unrealistic schedules and incomplete requirements. The first increment of the Block III Control Segment will implement only the capabilities available on the Block IIA, IIR, IIR-M, and IIF capabilities. Block III satellite operations will not be possible until the second of four increments. Furthermore, there is a desire to accelerate the launch of the first increment of GPS III satellites, which would require the implementation of the second increment of the Block III Control Segment increment within two years from contract award. While the requirements definition has not finished and the issuance of an RFP is already behind schedule, there is a push to have the RFP issued by December 2006.

These external pressures are setting the Block III Control Segment program up for future difficulties. It is not realistic to expect a five-fold increase in speed between contract award and operational capability without solid and complete requirements. It is more likely that requirements problems will prevent the Block III Control Segment—and probably the Block III Space Segment program as well—from adhering to their schedules. A lack of complete and well-defined requirements will probably cause integration problems as well. The outcome may be the continuation of the Control Segment lag that is evident in

Figure 5's split arrows through the System Engineering box, which show that the implementation of some requirements in the SORD and ORD occur in the following blocks' subsystems. If this pattern continues, the GPS program will not implement some Block III requirements until Block IV.

Block III Control Segment and Space Segment successes are necessary to satisfy the needs of customers and users. Without availability of the Block III satellites and the second increment of the Block III Control Segment, the GPS Wing will not be able to sustain GPS constellation. If GPS Wing anticipates an inability to reach the milestones for these two deliverables before launching all Block IIF satellites, the fallback contingency would require the acquisition of more of these satellites before the production line shuts down. Users would have to experience the wait for new capabilities again, and the GPS Wing would need to reallocate near-term funds for the purchase of more Block IIF satellites rather than apply them to Block III contracts.

## **2. Transition to an Entirely New Control Segment**

For the first time in its operation, the program is planning the most significant transition in the system's history that involves the replacement of the Control Segment's hardware and software in order to prepare for the addition of new capabilities. This immense technical challenge includes the daunting risk that something might not work correctly, thereby requiring the current system to serve as a back-up to prevent an interruption of service. The program has never faced a challenge that places the operation of the entire system at such risk. Previous challenges dealt with new block versions of satellites where the technical failure of a single satellite still left the GPS Wing with time to recover prior to the next launch. In order to mitigate schedule and constellation replenishment risk further, current launch practices have the Wing hold a previous version of satellite in reserve after launching the first new version of satellite. The Control Segment does not have this luxury because the Block IIF New Master Control Station (NMCS) must be ready to support the operation of

Block IIF satellites. Readiness depends on operator confidence in this system, because if the operators are not confident that it will function properly, they will not accept the new system. At the same time, the legacy MCS will not be able to command and control the new Block IIF satellites—if needed as a backup, the MCS would only be able to sustain the pre-Block IIF satellite constellation.

The GPS Wing already faces a tough financial climate after dealing with a past oversight that resulted in a lack of vendor support for the transition of NMCS hardware and software to operational use. The increase in the Block IIF contract scope to include Control Segment transition support cost the Wing precious funds. The vendor for the Block III Control Segment should expect to satisfy requirements for transition activities also.

### **3. Contractual Challenges for the Space and Control Segments**

The GPS operators were expected to command and control the GPS constellation using the NMCS before the turn of the millennium. The Block IIF contract designated the vendor as the single prime contractor and system integrator for its Space Segment and Control Segment deliverables. However, the vendor does little integration work as it attempts to overcome technical and schedule challenges for both major sets of deliverables.

Operators were also expected to take on new responsibilities for the Launch, Anomaly Resolution, and Disposal Operations (LADO) subsystem that will replace a cross-program system that was to be decommissioned already. The GPS Wing must now fund the operation of this older system alone because other satellite programs have ended their reliance on it and because the GPS Wing has yet to overcome its LADO subsystem development program challenges. Problems with ambiguous requirements have caused problems with design and coding, as well as with the verification of these unclear requirements.

Complicating matters more for the GPS Wing, the Block IIR satellite vendors find that they need to make changes to satellite flight software that

would make it incompatible with Block IIF Control Segment software undergoing test and evaluation. It would have been simpler and cheaper to modify the Control Segment software when the system was delivered and operational. An additional risk involves the loss of Block IIR satellite vendor corporate knowledge if that vendor must delay fight software modifications long enough to necessitate laying-off key technical personnel. These people may find other programs or employers to support. After the Block IIF Control Segment becomes operational, the Block IIR satellite vendor also might not be available via an active contract to work with Control Segment Support Division personnel to improve the interface between their subsystems.

## **F. CHAPTER SUMMARY**

This chapter summarizes the basic functions of the Global Positioning System (GPS) and its segments, and describes the breadth of stakeholders who have an interest in the system. It also describes the organization of the GPS Wing that includes an expanded description of the Systems Engineering Division and the Branches within that division that are responsible for various types of requirements engineering activities. These activities include the requirements engineering activities that involve the system stakeholders and the requirements documentation they influence, as well as the GPS Wing requirements management process. The Acquisition Program Baseline (APB) highlights the relationships between subsystem development programs and the capabilities that they promise. As this chapter concludes, these subsystem development programs have not progressed as envisioned, and there are several requirements integration issues that the program must address in order to deliver working subsystems and capabilities without further significant costs, delays, and technical challenges.

### **III. LITERATURE REVIEW**

#### **A. INTRODUCTION**

This chapter discusses GPS program requirements literature, and other requirements engineering literature that influences the GPS program's handling of its requirements. Because there are so many requirements sources that impact the GPS's development over its growing number of block upgrades, this chapter offers only a sample of GPS program requirements documents. This sample includes the Capabilities Development Document (CDD) provided by the GPS Wing's customers; the most recent System Specification (SYS) written by the GPS Wing; one of many Interface Control Documents (ICDs) and Interface Specifications (ISs), and requirements management guidance in the form of GPS Wing Operating Instructions (OIs). Other resources include guidance from the Software Technology Support Center (STSC) and technical documentation for the Dynamic Object-Oriented Requirements System (DOORS) database.

#### **B. ORGANIZATIONAL LITERATURE**

##### **1. Overview of GPS Requirements Sources**

GPS requirements sources are those documents and organizations identified in Figure 5 of Chapter II. These include the CDD and its predecessor documents, the ORD and SORD, as well as the hierarchy of specifications and ICDs that apply either to the overall system or to specific components of its segments such as a block of satellites. Other documentation that affects requirements development, management, and verification are GPS Operating Instructions (OIs). Two operating instructions are of particular interest to this research effort: the DOORS OI and the Requirements OI exist only in draft form as of September 22, 2006.

## **2. Capabilities Development Document (CDD) for the Block III Space and Control Segments**

The Capabilities Development Document will be a compliance document for the GPS Block III space and control segment contracts. This 440-page document signed by the 4-Star military leaders of Air Force Space Command (AFSPC) and the Headquarters U.S. Air Force (HQ USAF) presents system conceptual descriptions and gaps in capabilities that development efforts should close. Covered in the first section, Capabilities Discussion, these gaps are measured by comparing different environmental conditions in which the GPS might operate. Whereas the GPS operated effectively in non-hostile environments and those that existed during past military operations, environmental conditions have become less hospitable and the effectiveness of the GPS services has deteriorated accordingly. For example, the increase in non-GPS civil users of the frequency spectrum has adversely impacted civil users of GPS. Military users have also operated in environments that included harmful sources of interference to GPS. To overcome these challenges to operational capability effectiveness, the CDD serves to identify the highest system-level requirements that the GPS Wing will need to satisfy through its development programs. This CDD covers the subject areas shown in Table 2. The paragraphs that follow note the main themes in how requirements are stated throughout this CDD, but do not discuss specific requirements themselves.



<ul style="list-style-type: none"> <li>• Capability Discussion</li> <li>• Analysis Summary</li> <li>• Concept of Operations (CONOPS) Summary</li> <li>• System Capabilities Required for the Current Increment</li> <li>• Program Summary</li> <li>• Family of System and System of Systems Synchronization</li> <li>• Electromagnetic Environmental Effects (E3) and Spectrum Supportability</li> <li>• Schedule and IOC/FOC Definitions</li> </ul>	<ul style="list-style-type: none"> <li>• Threat Summary</li> <li>• National Security System and Information Technology System (NSS and ITS) Supportability</li> <li>• Intelligence Supportability</li> <li>• Assets Required to Achieve Initial Operational Capability</li> <li>• Other Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities, (DOTMLPF) Considerations</li> <li>• Other System Characteristics</li> <li>• Program Affordability</li> </ul>
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Table 2. GPS III CDD Subject Areas

The Analysis Summary section discusses results and scores for various capability solution alternatives. While some of the results discussed come from testing or simulation, subject matter experts relied on their experience to specify other results subjectively. This comparative analysis is interesting and perhaps useful to a vendor who would like to understand the rationale for some requirements—especially when requirements suggest a specific combination of technologies to be developed further in order to provide a capability. However, the analysis-of-alternatives discussions do not introduce clear requirements to satisfy. Instead, recommendations keep the government’s options open regarding how it will eventually define requirements. These recommendations include mention of the needs to conduct further analyses, which means that it is up to the Wing to develop the high-level requirements for the areas analyzed.

The CONOPS Summary explains what the customers and operators want in terms of the logical and physical architecture of the system that the GPS Wing will deliver. With the CDD as a compliance document, these expectations become real requirements. If the delivered system does not conform to the CONOPS, the customers and operators will declare the system to be operationally unsuitable, which in turn would result in the failure of the development program. In addition to this CONOPS Summary, there is an appendix to the CDD that expands on the GPS architecture with the *All Views*, *Operational Views*, and *System Views* of the Department of Defense Architecture Framework (DoDAF).

Requirements in the CDD are stated in terms of operational effect of the overall GPS. For example, Key Performance Parameters (KPPs) specify levels of PVT accuracy in units of meters, and availability of these levels of service in terms of percentages of time. Failure for a program to achieve a KPP could result in a decision to terminate that program. Many KPP values and system Threshold and Objective performance targets are defined in the 78-page CDD section titled System Capabilities Required for the Current Increment. This section includes quantifiable measures of system performance and rationale for the numbers chosen. The rationale can be useful to developers and customers alike as development of any part of the system continues and questions arise about the importance of achieving these goals. While some rationale explains operational needs, other rationale describes constraints in the form of laws or regulations that may change over time and, as a result, influence future program decisions.

There are many requirements that the GPS must satisfy in order to remain interoperable with external systems, or that other DoD systems must also satisfy. These are identified in the Family of System and System of Systems Synchronization section. Cross-DoD system requirements for Families of Systems are specified in Capstone Requirements Documents (CRDs) that cover the areas of interest identified in the following titles:

- Close Air Support (CAS)
- Combat Identification (CID)
- Global Air Traffic Management (GATM)
- Global Information Grid (GIG)
- Integrated Satellite Operations (SATOPS)
- Space Control.

These CRDs are compliance documents for the GPS program that cover various system functional and nonfunctional requirements. Each of the CRDs represents a *Family* that the GPS belongs to. *System of Systems* include augmentation systems and additional payloads for the GPS. Desired interoperability with space-based and ground-based GPS augmentation systems is important to support the improvement of GPS accuracy for civil users. The GPS also meets requirements to support the implementation of the non-PVT service known as the Nuclear Detonation (NUDET) Detection System (NDS), and may need to add requirements to support capabilities desired in the concept known as the Distress Alerting Satellite System (DASS).

The *Electromagnetic and Environmental Effects (E3) and Spectrum Supportability* section is noteworthy because of its simplicity and brevity. This section requires that subsystems in both the Space and Control Segments be able to operate effectively in their respective electromagnetic environments. It also requires that the GPS operate in compliance with both the ever-changing international and domestic regulations and policies that govern frequency spectrum use. Therefore, it is most practical to cite these requirements by reference and omit discussion of goals and rationale.

The section titled *Schedule and IOC/FOC Definitions* appears to contain no requirements, but in a document called a “Capabilities Development Document,” it seems appropriate that some terms related to these capabilities are defined in order to facilitate the statement of requirements within or beyond

the CDD. Of particular interest to GPS program managers, system engineers, customers, operators and users are the definitions of Initial Operational Capability (IOC) and Full Operational Capability (FOC). These definitions depend on the implementation of technologies in all three GPS segments.

While describing system-related requirements, several sections also include development-related requirements that are not requirements that the operational GPS would need to satisfy. These requirements are appropriate for a capabilities document that guides system development. Some of these, like Threat Summary and the Supportability sections describe issues that are important. These nonfunctional requirements issues cover system technical characteristics, performance, reliability, security, and usability. These sections are as follows:

- *Threat Summary*
- *National Security System and Information Technology System (NSS and ITS) Supportability*
- *Intelligence Supportability*
- *Assets Required to Achieve Initial Operational Capability*
- *Other Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities, (DOTMLPF) Considerations*
- *Other System Characteristics, such as*
  - Hazardous Materials
  - Safety and Health
  - Security Classification Guidance
- *Program Affordability*

These sections include system requirements, especially in the case of personnel and facilities that are critical parts of the Control Segment. Many of the types of

requirements in these sections include threshold values that equal their objective values, thereby showing that the requirements are either satisfied or they are not.

### **3. System and Segment Specifications**

The specifications documents focus on system and subsystem requirements that support the delivery of a subset of required capabilities described in the CDD. These documents are different than the CDD in their organization and their focus. They contain a more detailed view of the system, its performance, and the specific user needs to be satisfied. System Specifications (SYS) and Segment Specifications (SS) are similar in their structure. A description of the Space and Control System Specification follows below.

In order to avoid redundancy, the GPS III Space and Control Segment's System Specification names 103 other requirements documents as sources of requirements that must be satisfied. These sources include the following items:

- DoD Handbooks and Standards
- Air Force Directives, Instructions, Manuals, and Pamphlets
- DoD Directives, Instructions and Manuals
- GPS Wing Documents (ICDs, ISs, the Program Protection Plan, and Computer Resource Support Plan)
- GPS Modernization System Threat Assessment Report (STAR)
- Agreements with federal agencies and international organizations
- Miscellaneous aviation, frequency spectrum, acquisition, safety, security, design, test, certification, and operational guidelines and standards
- Specifications and reference documents from other agencies and programs

These documents fall into two categories: 1) compliance documents that are to be treated as an extension of the SYS, and 2) reference documents that can act as guides or sources of other relevant information. To prevent any problems with requirements ambiguity, the SYS states that its guidance supersedes any requirements that are in conflict with the SYS. Lower tier requirements (below the CDD) comply with the following order of precedence:

1. System Specification (SYS)
2. Segment Specification (SS)
3. System-Level Interface Control Documents (ICDs) and Interface Specifications (ISs)
4. Segment Product/Development Specifications

A brief system description section describing the functions and capabilities of the next generation Space and Control Segments precedes the discussion of GPS III system-level requirements that contain '*shall*' statements. Even though this SYS is not a User Segment specification, it describes system performance in terms that are relevant to user equipment measurements like pseudorange and calculations like PVT information. Requirements statements also address other user concerns, such as the level of availability of GPS services. For services that do not exist, effectivity is used to help describe the incremental deployments of capabilities in the SYS. For both the Space and Control Segments, there are four effectivities, or increments, defined in this SYS. Only the final full-capabilities effectivity definition for each of these two Segments matches. Because the Control Segment's subsystem is not up to date, the first Block III Control Segment increment addresses only unsatisfied requirements from the ORD that the CDD absorbed.

In addition to increasing the breadth and quality of services, the GPS must also continue providing the current services. In order to do so, new parts of the GPS Segments must maintain the current external interfaces, and either replace or continue to support internal interfaces with existing Segment subsystems. The

GPS has external interfaces with additional GPS satellite payloads and systems that belong to non-AFSPC organizations like those described in Figure 5. GPS internal interfaces connect the various GPS Space Segment vehicles with each other, the Control Segment, and the User Segment.

The remaining requirements are nonfunctional and address the following areas of concern:

- Safety
- Security
- Computer
- Environmental
- Quality
- Design & Construction
- Personnel
- Training
- Logistics
- Packaging, handling, storage, and transportation

These are all important nonfunctional requirements that have an impact on the successful fielding of new capabilities.

A Quality section discusses the methods for verification of requirements to ensure that the system will meet its performance criteria, comply with design characteristics, satisfy interface needs, and operate properly. System Engineers and Program Managers can verify requirements using the following methods to be tracked for each requirement in the DOORS requirements database:

- Inspection
- Analysis
- Demonstration
- Test
- Special methods to provide aviation safety assurance.

The government specification documents often use the word *shall*, but there is no current government source that restricts the use of this word or defines what it means when compared to other words like *must* and *will*. Vendors find it necessary to provide definitions for these terms in order to prevent any conflicts from arising about their meanings. At the beginning of its software requirements specifications (SRSs) written under contract for Boeing Navigation Systems, Lockheed Martin Integrated Systems and Solutions (Gaithersburg, MD) provides definitions that are paraphrased below:

- A '*shall*' statement identifies all requirements or parts of requirements that trigger design, coding/production, and unless otherwise stated, testing. A '*shall*' statement has a unique number for identification and traceability.
- A '*must*' statement identifies a requirement that is one of two things:
  - a system design constraint
  - or
  - a provision being provided to the designer by the government and upon which the designer depends--government furnished property (GFP) or equipment (GFE).
- A '*will*' statement is used like a '*must*' statement for instances in which the government is to provide GFP or GFE, but the system being designed does not depend on this property or equipment.

Because there is no need for unique identification or traceability, '*must*' and '*will*' statements are not numbered.

#### **4. Interface Control Documents (ICDs) and Interface Specifications (ISs)**

GPS program uses ICDs and ISs to describe the interfaces between GPS subsystems. There are external interfaces with systems belonging to other



organizations, and there are internal interfaces that describe the characteristics of the information exchanged between different GPS Segments' subsystems. Dozens of these ICDs and ISs describe internal interfaces, and while the government controls some of these interface documents, contractors exercise control over others. This section discusses the government-vendor conflict over these documents, and describes the structure of one of the interface documents.

**a. *The Emergence of ISs in the GPS Wing***

Current practice establishes the Interface Control Contractor (ICC) for a given ICD as one of the vendors for two new subsystems that will interface. For example, an ICD describes the interface between the Block IIF Control Segment and the Block IIR satellites. The Block IIR satellite vendor is the ICC for this interface. Problems with ICC control over ICDs prompted changes to how the GPS Wing baselines interface descriptions. As a result of these problems, a previous GPS Wing Commander decided to change how the GPS Wing handled certain interface documents.

Vendors took exception to changes proposed for ICDs that described GPS signals. Because ICDs require the affected parties to agree to changes, and agreement requires that the parties provide their signatures on Interface Revision Notices (IRNs), the lack of vendor signatures on these ICDs prevented the GPS program from implementing necessary changes to signal descriptions. The GPS Wing Commander attempted to regain control over these ICDs by changing the names of these documents to Interface Specifications and treating them the way that the Air Force Satellite Control Network (AFSCN) treats its own ISs—the AFSCN issues changes to ISs without ensuring that the affected parties approve of the changes (Alexander, P., personal communication, August 31, 2006). In the case of the AFSCN, it is infeasible to gain approval from all affected parties because there are so many. The GPS Wing Commander implemented the same approach by arranging for some ICDs to become ISs because it is also impractical to get the approval of so many GPS users when

changing ICDs might affect them. The GPS Wing Commander argued that if users did not provide their consent to ICD changes, then vendors would not need to consent to interface changes either. Therefore, ICDs describing the interface between one-subsystem and many affected parties became ISs. The structure of an IS is the same as that for an ICD. ICDs continue to describe one-to-one interfaces and require signatures from each of the two affected parties when there is an agreement on changes.

The emergence of ISs in the GPS Wing did not solve all contractual problems with vendors. The GPS Wing found it necessary to include ‘*shall*’ statements in ICDs and ISs so that vendors would ensure that their deliverables would interface with existing GPS subsystems properly. Without ‘*shall*’ statements in interface documents that require verification testing, vendors considered such testing to be beyond the scope of their contracts. Instead of defining and describing interfaces with the least amount of ambiguity possible—perhaps by offering detail and background information—GPS program ICDs and ISs go beyond providing descriptions by stating requirements for vendors to satisfy. According to SETA contractor Patricia Alexander, “good old engineering common sense should lead to verification tests,” but without a ‘*shall*’ statement, the vendors’ business managers will not agree to verify that their deliverables will interface with other GPS subsystems correctly (Alexander, P., personal communication, August 31, 2006).

#### ***b. Space-to-User Interface Specification***

SETA contractor ARINC is the ICC for the IS that describes the interface between the Space Segment and the GPS navigation users who belong to the User Segment. Because this document is for an internal interface, there are no external specifications or standards that apply. This document focuses on Space-to-User requirements exclusively.

This IS describes the carrier frequency, ranging code, signal structures, navigation signal, and other signal characteristics of interest to two

important categories of GPS stakeholders who work with their GPS Wing counterparts: 1) user equipment developers who must process GPS signals, and 2) satellite developers who must provide the signals. In addition, there are also many definitions and equations provided to ensure a common understanding among these two groups of stakeholders so that they develop subsystems that are compatible. Going beyond the description of the interface, there are several '*shall*' statements in this document that require both interfacing subsystems to support specified levels of service.

As a result of changes to this IS, vendors submitted Letters of Exception (LOEs) to state their non-concurrence with proposed changes that became approved. Even though the GPS Wing approves ISs unilaterally, the Wing chose to provide some of the LOEs in the IS in order to document the vendors' concerns publicly. These vendors based their exceptions on cost, schedule, or performance impacts that would result if—in order to satisfy newly-baselined requirements—the vendors needed to increase the scope of their efforts beyond the scope defined in their contracts. Vendors submit these letters because they need to justify the impact of changes. The GPS Wing can respond to these letters in a few ways:

- The GPS Wing can authorize a Letter of Exception to stand and document it in the IS revision,
- The GPS Wing can reject the letter and pursue contractual discussions to resolve the issue
- The GPS Wing can agree to provide some form of relief to the vendor that submits the letter.

## **5. GPS Operating Instructions (OIs)**

There are two draft GPS Wing OIs that are especially relevant to this paper: 1) the draft DOORS OI for the Dynamic Object-Oriented Requirements System tool used by the government and vendors for the GPS program, and 2)

the incomplete draft Requirements Engineering OI. These will be used together in order to guide GPS program requirements development, management, and verification.

**a. DOORS OI**

The Requirements Branch of the Systems Engineering Division maintains the DOORS database, capturing requirements and allowing this database to interact with those DOORS databases of the vendors who also use this tool. This requirements management tool is widely-used for complex systems like the GPS.

Of the two ways in which a development program can manage requirements in DOORS, the GPS program uses the document-oriented approach specified in the draft GPS DOORS OI. “GPS has adopted a document-based approach whereby DOORS modules are created that map one-to-one to the program’s documents” (Chief Engineer GPS Wing, 2006 draft). The draft OI also directs the GPS program to place each requirements document into a separate module. All modules are linked in a hierarchy. Objects within modules exist for each section heading and requirement paragraph. Related modules can be grouped into DOORS Projects, such as for a segment subsystem of the GPS like Modernized User Equipment (MUE) or the Block IIF Control Segment.

Because some requirements are classified, the draft DOORS OI requires that an up-to-date duplicate of the GPS DOORS database reside on a stand-alone computer located in an appropriately secure vault. In addition to the duplication of unclassified GPS requirements, this separate database includes all classified requirements with all of the links necessary to trace up to higher-level requirements or assess impacts on lower-level requirements. Access to this classified database and the classified requirements that populate it is limited to those who have the appropriate security clearances and need-to-know.

DOORS attributes help to clarify and categorize requirements information captured in objects. The draft GPS DOORS OI Attachment 8 recommends that each program adopt the definable attributes listed in Table 3.

<ul style="list-style-type: none"> <li>• Segment/Block Allocation</li> <li>• Classification level</li> <li>• “Is” Requirement (T/F?)</li> <li>• Performance Area <ul style="list-style-type: none"> <li>– Accuracy, Integrity, etc.</li> </ul> </li> <li>• Technical Performance Measure</li> <li>• Requirement ID <ul style="list-style-type: none"> <li>– Only for objects containing a reqt</li> </ul> </li> <li>• Requirements POC</li> <li>• Risk <ul style="list-style-type: none"> <li>– Low, medium, high</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Verification Method <ul style="list-style-type: none"> <li>– Analysis, test, demo, etc.</li> </ul> </li> <li>• Verification POC</li> <li>• Verification Status <ul style="list-style-type: none"> <li>– Verified, not verified, passed, failed</li> </ul> </li> <li>• Verification Level <ul style="list-style-type: none"> <li>– System, Segment</li> </ul> </li> <li>• Priority <ul style="list-style-type: none"> <li>– KPP, non-KPP</li> </ul> </li> <li>• External Reference <ul style="list-style-type: none"> <li>– Links to non-DOORS doc.</li> </ul> </li> <li>• Rationale</li> <li>• Comments</li> </ul>
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Table 3. Draft GPS Wing DOORS OI Recommended Attributes

In addition to the recommended attributes, assigned attributes include such characteristics as the object’s creator, creation date, and last modification date.

For example: The Requirement ID attribute is a unique identifier for each requirement. The Requirement ID attribute remains blank for non-requirement objects, and a sorting feature allows for a document’s (or module’s) requirements to be identified and presented in a view that does not include the other objects.

As requirements change, additional attributes can help to track these changes. Changes are managed using the GPS Wing requirements management process that supports the Configuration Control Board (CCB), as shown in Figure 6 and repeated as Figure 7 below. The CCB can only control the requirement Verification Method and Rationale attributes. Other helpful attributes include the 'Was' Requirement attribute to identify the previous wording of a requirement, the Proposed Change attribute to identify the proposed wording, Reason For Change text attribute, and the Attribute/Link Change Summary attribute to summarize changes to existing requirement attributes as well as changes to the links to other requirements.

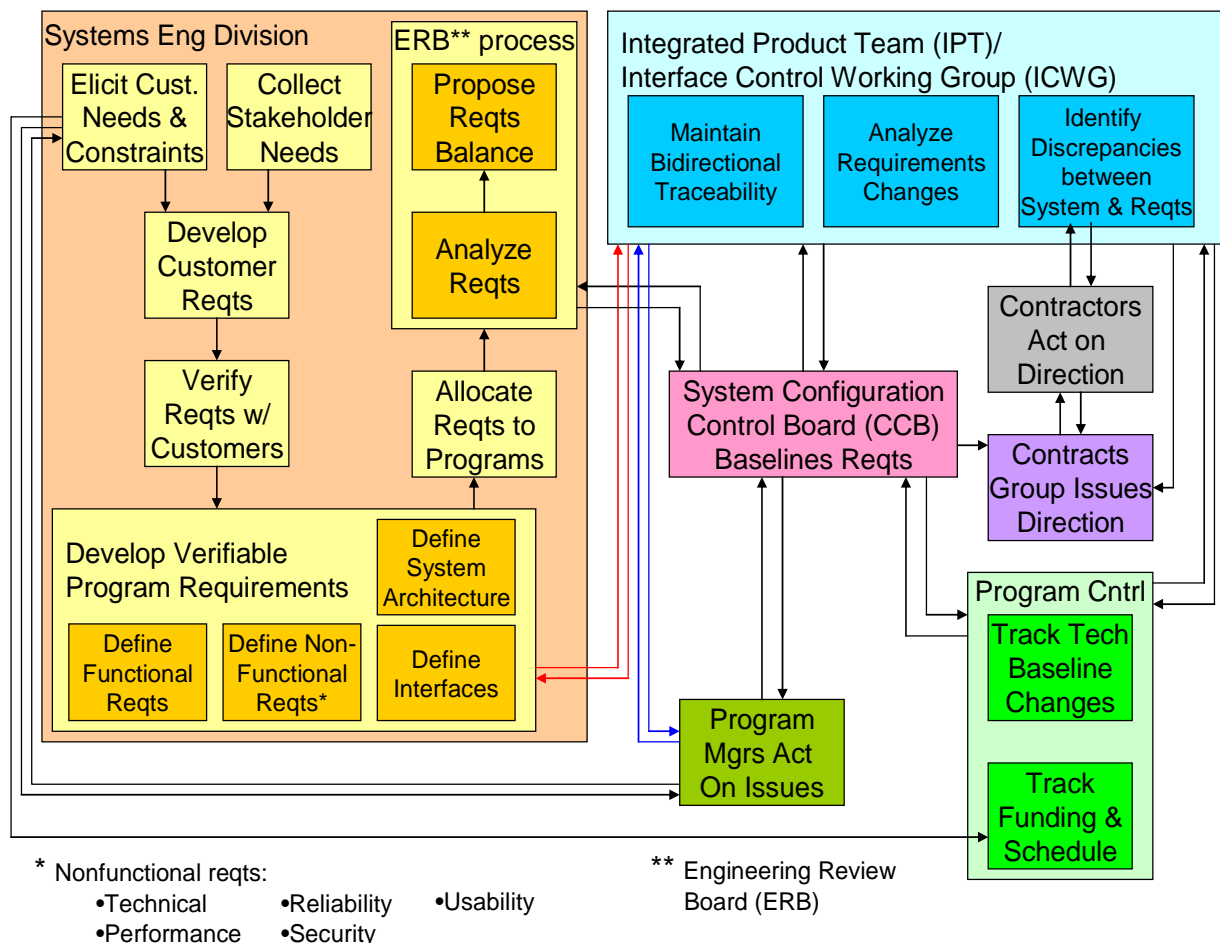


Figure 7. GPS Wing Requirements Management Process (After Chief Engineer Navstar GPS Joint Program Office, 2006a, 2006c).

The OI also requires the inclusion of the Contract Data Requirements List (CDRL) items in DOORS. The CDRL items shall include the following documents:

- The System Specification
- Segment specifications
- Prime item development specifications that trace requirements to their respective higher-level specifications
- Interface Control Documents (ICDs)
- Test plans, procedures and reports (to support verification of specification requirements)

Linking is a powerful DOORS feature that facilitates requirements analyses. Traceability and impact analyses deal with external links that focus on requirements relationships up to parent modules (or documents) and down to child modules. The OI requires the appropriate steps to avoid describing requirements in ways that complicate the ability to link objects that contain requirements. One example includes the requirement for DOORS modules to refrain from using compound requirements, which are multiple requirements attached to only one '*shall*' statement. Such statements should be broken apart into individual '*shall*' statements and then re-linked to show the relationship between them. Another example is to use DOORS tables in which each cell contains no more than a single requirement. When it is not possible to capture a requirement fully in a single '*shall*' statement, then the most effective practice is to establish internal links (or links within a module) to explanative objects that do not contain '*shall*' statements. These objects can include tables, figures, equations or other sources of information that help to describe the requirement fully. Besides traceability and impact analyses, other analyses related to links include finding orphan requirements objects and suspect links. Orphan requirements do not have parent requirements to satisfy. Suspect links can

emerge when the contents of linked objects change, and as a result, give reason to question the validity of the links to those objects.

When approved, the DOORS OI will require that DOORS users to refrain from using generic DOORS links. Instead, GPS DOORS users will use requirements links to connect requirements objects in different modules. Similarly, DOORS users will also use test and verification links to connect test and verification data to higher-level requirements objects. The ability to define different types of links allows DOORS users to either trace through requirements objects or find test and verification objects more quickly. Finally, special links shall be defined for various situations as needed, including the linking of proprietary documents and also for linking internal GPS Wing documents for Wing use only.

In addition to describing the utility that the DOORS database can provide, the OI also discusses other issues that are mainly DOORS technical issues rather than functions it performs. These issues include configuration management, module output formats and reports, technology and administrative support, management, and user training. An important technical issue that affects the effectiveness that DOORS can have for a program involves the details of how to prepare documents for DOORS importation. Most often these files will be Microsoft Word or Excel documents. Often these documents will include figures and tables that must be handled appropriately in order to facilitate linking the information to other documents/modules. For example, each cell within a DOORS table for a given module can be linked separately to other modules.

Lastly, the draft DOORS OI explains the roles and responsibilities for the following program personnel and organizations:

- DOORS Management Working Group (DMWG) lead by the DOORS Government Project Lead
- DOORS Information Technology Support
- DOORS Configuration Manager and Training Liaison Manager



- System Engineering Lead
- Program Management Lead
- DOORS Module Points of Contact, and the Integrated Product Teams Coordinator who assigns them
- Interface/Specification Control Contractors
- Program Managers
- Configuration Control Board Reviewers
- DOORS users

The people who occupy these roles and participate in these groups are charged with ensuring that the GPS program requirements are captured fully, that proposed baseline configuration changes are tracked, and that updates are made when proposed changes are approved. The government also works with vendors to ensure that the vendors' DOORS database technology and practices remain compatible in order to support the exchange of DOORS information.

While the DOORS OI draft was available for review on March 23, 2006, the GPS Chief Engineer and GPS Wing Commander have not implemented this document as policy as of September 22, 2006. While the review of this draft continues, the GPS program also faces information technology funding challenges that will limit the effectiveness of this policy. The GPS Wing currently has 21 licenses for this database tool to share among even more customers, vendors, and other stakeholders. The GPS Wing also lacks funding for the classified workstation to handle classified requirements.

#### ***b. Requirements Engineering OI***

At the time of publishing for this thesis, which will be completed by September 22, 2006, the Requirements OI existed only in draft form. The draft guidance emphasizes the requirements functions and associated processes for

carrying out these functions thoroughly. The three requirements engineering functions are listed in Table 4 below:

• Requirements Development	• Requirements Management	• Requirements Verification
– Identifying stakeholders & their needs	– Establishing resources	– Verifying products
– Synthesizing requirements	– Establishing requirements providers	– Establishing & maintaining verification environment
– Prioritizing & categorizing requirements	– Capturing information	– Verifying procedures
– Validating requirements	– Managing change	– Using peer review process
– Developing a high-level baseline	– Creating products	– Verifying products
– Documenting requirements	– Managing supplier documentation	– Assisting supplier verification
		– Updating JPO System Eng. Plan (SEP)

Table 4. Requirements Engineering Functions listed in OI.

The draft DOORS OI emphasizes all three groups of functions described in the Requirements OI. While much work remains before this OI is complete and approved, the intent appears to include supporting GPS program needs by ensuring well-defined requirements to populate the DOORS database.

The draft Requirements OI also includes a checklist for systems engineers to use when writing requirements. The checklist includes the following questions about potential requirements statements:

- Is it clear?
- Is it as short as it can be?
- Does it apply to a defined type of user?
- Does it have a reasonable priority?
- Is it verifiable?
- Is it a single requirement?
- Is its source shown?
- Does it have a unique identifier?
- Is it genuinely a user requirement, not a design constraint?

(Chief Engineer GPS Wing, 2006 rough draft)

This checklist will guide engineers and program managers who may not remember the characteristics of a good requirement. It will also help to encourage a consistent level of requirement statement quality across GPS subsystem acquisition programs.

## **C. REQUIREMENTS ENGINEERING LITERATURE**

### **1. Software Technology Support Center (STSC)**

Jim Van Buren and David A. Cook of Draper Laboratory and the Software Technology Support Center provide a history of requirements engineering challenges and lessons learned in their paper titled *Experiences in the Adoption of Requirements Engineering Technologies*. They categorize requirements engineering into the following five categories:

1. Elicitation – getting customers to state their exact requirements
2. Analysis –
  - a. making qualitative judgments about system requirements

- b. beginning a high-level design by decomposing the system into components and specifying their interfaces
- 3. Management – dealing with requirements changes
- 4. Validation and Verification –
  - a. Validation – building the right system (to satisfy customers)
  - b. Verification – building the system right (to satisfy requirements)
- 5. Documentation –
  - a. structuring written specifications
  - or
  - b. choosing and structuring a requirements database

A major challenge facing many programs is the reality that many customers' view of requirements differs from that of developers. Whereas developers see a requirement as something that is testable and may be prioritized, many customers think of requirements in terms of their overall needs. Skilled requirements elicitation from customers helps to overcome this barrier to defining good requirements for developers.

There are many well-established approaches to requirements analysis, as well as tools to complement these approaches. These approaches include requirements modeling techniques such as traditional structured analysis and object-oriented analysis. (In spite of its name, DOORS is not an object-oriented analysis tool.) Even with proven tools and approaches, programs run into difficulties when tools enforce a process that is inconsistent with a development program's process, or when the people who implement the approach and tool lack sufficient training to be effective with them. Van Buren and Cook note that well-funded programs typically overanalyze requirements while other programs tend to analyze requirements less to save precious funds.

The requirements management portion of the STSC paper addresses how increased requirement volatility also increases programmatic risk. While volatility is a natural result when building a useful product, it is desirable to control volatility that results from the poor elicitation and specification of requirements. Requirements management tools can help track and measure requirements volatility, and also support the traceability and impact analyses up and down a requirements hierarchy. These tools provide information that should not only support internal programmatic decision making, but also the important interaction with customers who need to understand the impacts of requirements changes.

Developers should plan requirements validation and verification as early as the elicitation phase. Customers and users will not accept a system if it doesn't meet their expectations, so developers must elicit those requirements that are necessary to ensure that the right system is built. This validation is one measure of requirements quality. The other measure is requirements verification. If requirements are not verifiable, it will be impossible to demonstrate that the system is built correctly. The customers and users are essential to ensuring system validation and verification.

Requirements documentation involves specifying "an overall description, external interfaces, functional requirements, performance requirements, design constraints, and quality attributes" (as cited in Cook & Dupaix, 1999). These are explained in sources like withdrawn DoD standards MIL-STD-2167A and MIL-STD-498, as well as industry standards like ANSI/IEEE-STD-830-1993 and EIA/IEEE 12207. Requirements management tools can also support requirements documentation needs.

## **2. DOORS Database Documentation**

The Dynamic Object-Oriented Requirements System (DOORS) database is a Telelogic product that is widely used for managing requirements of complex development programs in industries like aerospace and defense. Using modules

and objects within DOORS, the GPS program uses this database product to store and track program requirements. Among this tool's strengths are the traceability and attributes features.

Modules are files that are used to capture requirements about an area of concern. For example, the GPS program uses separate files for each system specification and segment specification. All lower-level specifications are also separate modules that are linked to higher-level modules, as appropriate, in order to enable requirements traceability or impacts analyses. Objects in DOORS are distinguishable entities within modules, and these have unique DOORS identification numbers assigned to them automatically.

As Figure 8 below shows, if all GPS III requirements were loaded into DOORS and linked properly, it would be possible to look at the GPS III System Specification to see which requirements statements at different levels are related. In this notional example, traceability analyses help to ensure that the implementation of lower-level requirements results in the required subsystem or overall system performance. Similarly, impact analyses allow one to see how changes made to objects in higher-level modules will affect objects in lower-level modules. The person conducting the traceability and impact analyses can also choose the depth, or number of levels, that are of interest in either type of analysis. For example, one may only wish to see immediate requirements traces or impacts that go no further than one module up or down, respectively. With computer mouse clicks, both of these features allow the DOORS user to move from object to object across modules in order to access related requirements.

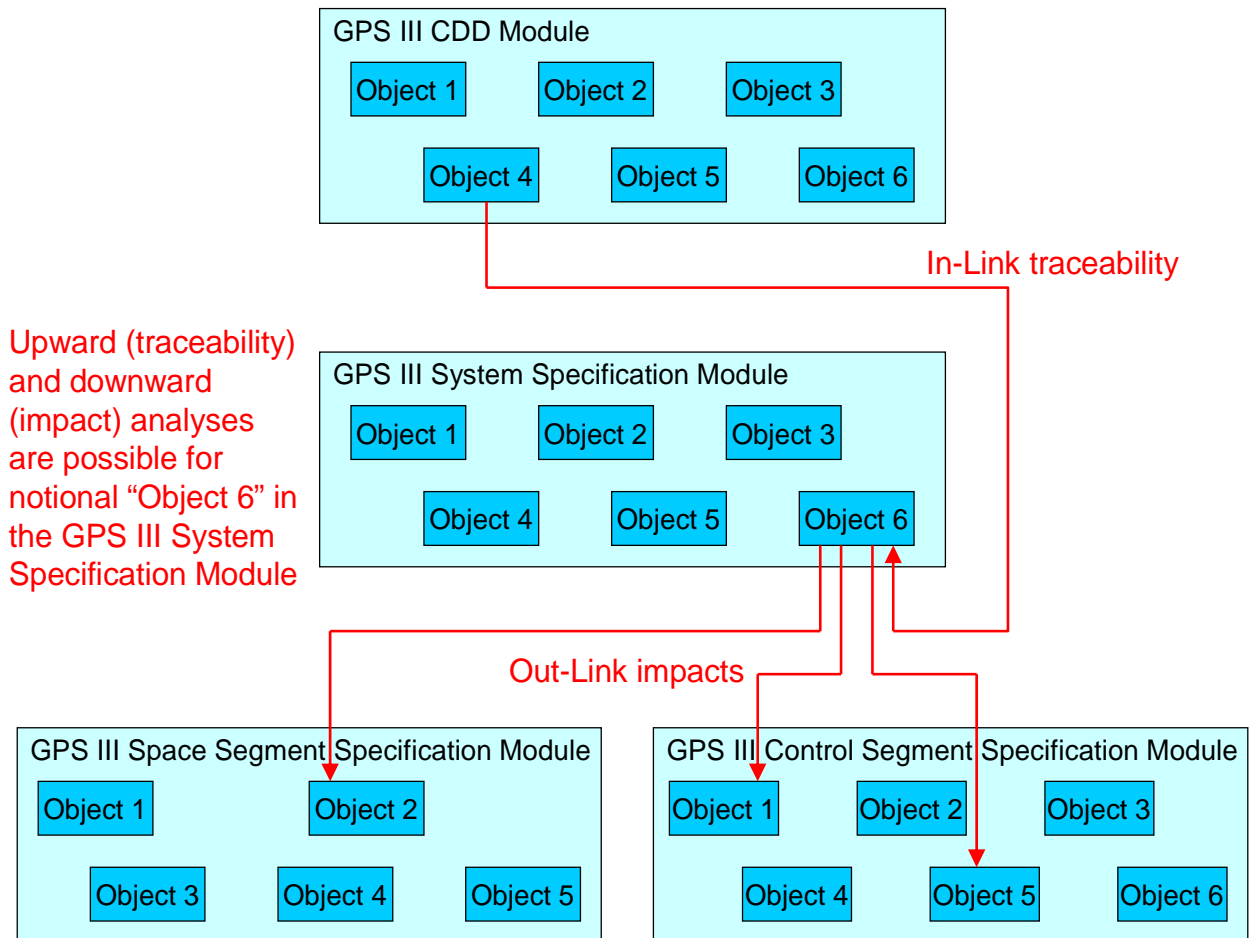


Figure 8. Notional GPS III Example of DOORS Traceability and Impacts.

In addition to linking requirements, it is easy to include other important information in DOORS to support system acquisition activities. In particular, modules and objects can capture design and test information. When linked properly, it is possible to trace test events to the design features to be verified, and continue to the requirements that the design features are to satisfy.

When creating links, it is possible to define different types of link characteristics in link modules:

- Many-to-many: each object can have many in-links and out-links

- Many-to-one: each object can have many in-links, but only one out-link
- One-to-many: each object can have only one in-link, but many out-links
- One-to-one: each object can have only one in-link and one out-link

Link module subdivisions called linksets include information about the links from one module to another or within modules. When dealing with only two modules, four linksets define links from Module 1 to Module 2, Module 2 to Module 1, Module 1 to Module 1 (for links between objects in Module 1), and Module 2 to Module 2. The direction of links is important, as shown in Figure 8. While there is a default DOORS link module, it is also possible to define different types of link modules for different purposes in order to improve organization, facilitate analysis, or limit user access.

DOORS objects have the ability to be described by up to 32 attributes. Attributes are characteristics that some requirements will likely share, and some of these are determined by the DOORS database while others are chosen by the system engineer who manages DOORS. The modules that include objects can have an unlimited number of attributes to pass on to the objects within the modules.

Tables 5 and 6 show the types of attributes and attribute types that one can expect to find in DOORS. While it is possible to edit some of the system attributes for either modules or objects (shown in italics), others are read-only. In addition to system attributes and DOORS-preset attribute types, there are also user-defined attributes and attribute types. The information contained within Tables 5 and 6 comes from the Help menu provided in Telelogic AB's DOORS 7.1 database. This Help menu serves as a comprehensive DOORS 7.1 users manual.



<u>System Attributes for Modules</u>	<u>System Attributes for Objects</u>
<ul style="list-style-type: none"> <li>• Created By</li> <li>• Created On</li> <li>• <i>Description</i></li> <li>• Last Modified By</li> <li>• Last Modified On</li> <li>• Mapping (one-to-one or many-to-many; only for link modules)</li> <li>• <i>Name</i></li> <li>• <i>Prefix</i></li> </ul>	<ul style="list-style-type: none"> <li>• Absolute number</li> <li>• Created By</li> <li>• Created On</li> <li>• Created Thru</li> <li>• Last Modified By</li> <li>• Last Modified On</li> <li>• <i>Object Heading</i></li> <li>• <i>Object Short Text</i></li> <li>• <i>Object Text</i></li> <li>• (advanced system attributes that show status information)</li> </ul>

Table 5. System Attributes for Modules and Objects.

<u>Base Attribute Types</u>	<u>User-Created Attributes</u>
<ul style="list-style-type: none"> <li>• Text</li> <li>• String</li> <li>• Integer</li> <li>• Real</li> <li>• Date</li> <li>• Enumeration <ul style="list-style-type: none"> <li>– this allows attribute to take on one of a predefined set of values</li> </ul> </li> <li>• Username</li> </ul>	<ul style="list-style-type: none"> <li>• Kilogram <ul style="list-style-type: none"> <li>– Base type Integer</li> </ul> </li> <li>• Dollar <ul style="list-style-type: none"> <li>– Base type Integer</li> </ul> </li> <li>• Percentage <ul style="list-style-type: none"> <li>– Base type Integer</li> </ul> </li> <li>• Deviation <ul style="list-style-type: none"> <li>– Base type Real</li> </ul> </li> <li>• Priority <ul style="list-style-type: none"> <li>– Base type Enumeration</li> </ul> </li> <li>• Rationale <ul style="list-style-type: none"> <li>– Base type String</li> </ul> </li> </ul>

Table 6. Attribute Types—Base & Some Possible User-Created.

DOORS allows the ability to take user-defined attributes from other modules and import them into the module a user is working on. In the case of GPS, it could be helpful to use existing module and object attributes defined for an existing block of space vehicles to help describe the requirements for the corresponding DOORS objects and modules used for future block acquisition programs.

#### **D. CHAPTER SUMMARY**

This chapter reveals the various requirements engineering literature that is available to the GPS program and to the broader systems development community. While it is important not only to define a development program's system requirements clearly, it is also important to organize and manage these

requirements effectively so that program managers and systems engineers can support the design and verification of systems. It is also important to implement methodologies—a combination of models, tools, and techniques—that are aligned with these requirements engineering activities rather than disrupt them. The DOORS database is a tool that is aligned with the GPS Wing's requirements practices. The database attributes, linking, and traceability features allow users to store and organize information in a way that supports analysis and decision-making. The next chapter addresses the implementation of these ways to improve how the GPS program handles all three areas of its requirements engineering activities: requirements development, requirements management, and requirements verification.

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## **IV. RESEARCH ANALYSIS AND RECOMMENDED APPLICATION OF STUDY**

### **A. INTRODUCTION**

The literature reviewed and the interviews conducted with GPS Wing personnel serve as the foundation for this chapter. Recommendations span the requirements engineering activities that include how the GPS program elicits, stores, manages, evaluates, and changes its program technical baseline. This chapter attempts to answer as completely as possible the research questions posed in Chapter I. Many of these conclusions demonstrate that effective solutions do not necessarily require new material solutions like a new database. Some changes in institutionalized practices alone offer new possibilities for improving requirements engineering and decision-making agility. The Dynamic Object-Oriented Requirements System (DOORS) is a capable requirements management tool in use by the GPS Wing. While any tool has room for improvement, DOORS is adequate for the manner in which it is used, has been successful in the past, and has a tremendous amount of untapped potential to support the GPS program requirements engineering needs.

### **B. CHANGING TO A REQUIREMENTS-CENTRIC APPROACH**

As shown in Figure 5 and repeated as Figure 9 below, the GPS Wing elicits its requirements from the Headquarters of the U.S. Air Force (HQ USAF), Air Force Space Command (AFSPC), U.S. Strategic Command (USSTRATCOM), and the Interagency Forum for Operational Requirements (IFOR). These organizations provide their inputs by means of documents that exist to serve a broad audience of systems engineers, program managers, customers, and users. The format of these documents makes them useful to all, but it is not a format that is most practical for the engineers and managers who access the requirements and study them meticulously. The chapter, paragraph and sentence structure may appeal the most to the customers because it is

familiar, but this structure makes it more difficult for engineers and program managers to organize their requirements in order to ensure they deliver the product that the customer wants. With a requirements-centric use of the DOORS database tool for the GPS program, the GPS Wing could streamline its requirements engineering activities and reap benefits that go from development activities through design verification and system deployment. However, the GPS Wing has no plans to demonstrate and take advantage of this model. The draft DOORS OI shows that the GPS Wing will follow the document-centric model, which follows the lead of AFSPC after it refused to provide a requirements-centric CDD (Campbell, J., personal communication, July 25, 2006).

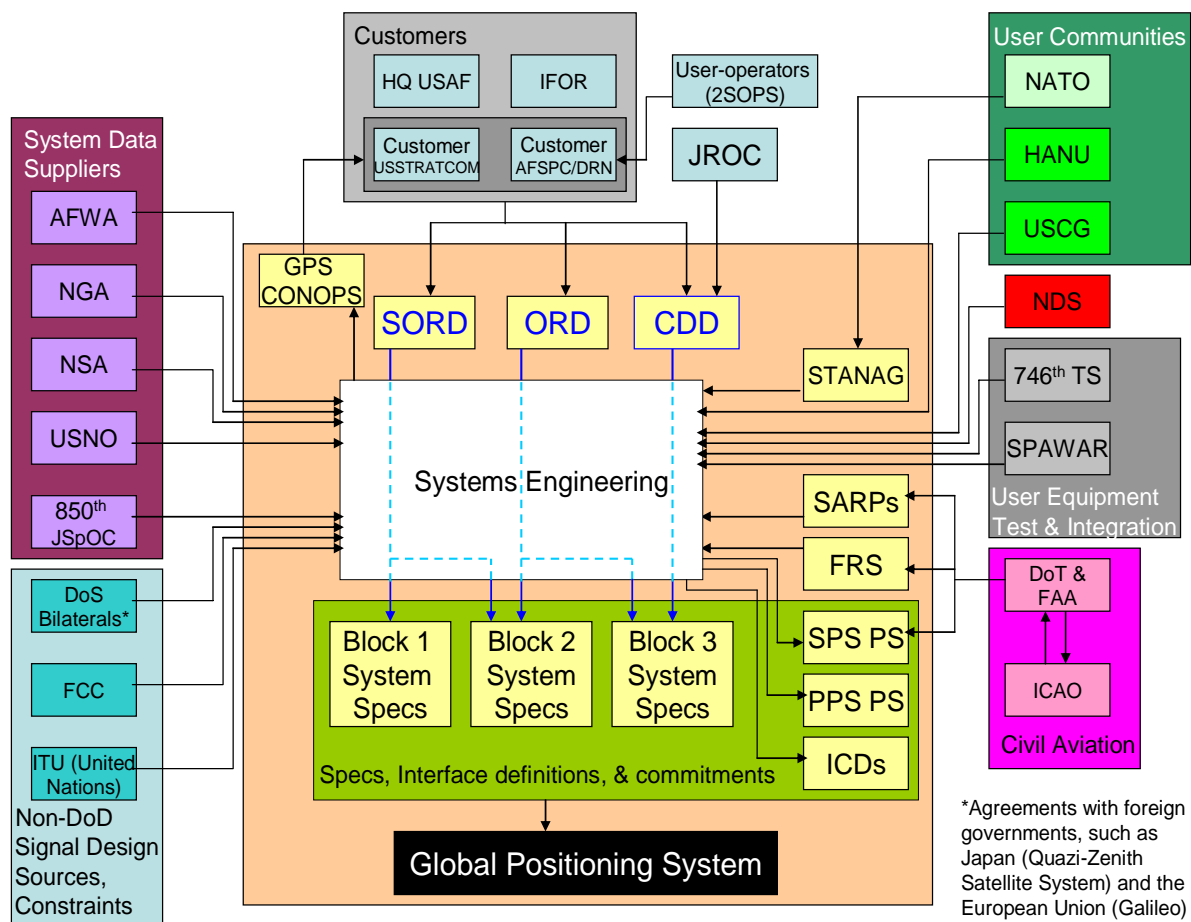


Figure 9. GPS Requirements Documents and Requirements Sources (After Alexander, 2006; and After Chief Engineer Navstar GPS Joint Program Office, 2006c)

The DOORS database stores specification information in a manner that mimics each document's structure. Users treat it as a document repository. For these documents, each of which is a DOORS module, the objects are arranged in the order they appear as headings or paragraphs in the source document. As used by most GPS Wing account holders, DOORS offers no advantage over using the source requirements documents themselves. The lack of links between requirement objects and the limited use of user-defined attributes prevents anybody from conducting queries that would otherwise help to trace, filter, or sort through requirements objects of interest. Thus, these users are not exploiting the most powerful features that DOORS offers.

Current users have exposed another flaw with the document-centric approach that prevents them from exploiting the capabilities of DOORS. Because they see a format for information that mimics the source documents, users tend to expect to have word processing and spreadsheet functionality that allows editing. For example, Microsoft Word and Excel source documents must be updated first before uploading the entire blocks of text or entire tables as DOORS objects to replace the existing objects. The need to perform this kind of procedure causes some to question the value of the DOORS tool, but this user expectation is evidence of a DOORS tool education problem and an implementation weakness that results from the document-centric approach specified in the draft GPS DOORS OI. These users do not appreciate the capabilities of databases in general.

The requirements engineering goal for the GPS program should be to do away with the various requirements documents it tracks, and instead focus on the structure of the system's requirements. Much of the information contained in these documents is background information that does not describe requirements that the program must satisfy for its customers. This information could go into documents that provide background information, but it should not get mixed with new requirements because of the problems that can and do result from the

ambiguity regarding whether a statement is a requirement or not. Requirements are not all listed together in the current documents.

Because it is in wide use by vendors and the GPS Wing, the DOORS database is available and able to support building requirements hierarchies that can take over the requirements roles played by capability and specification documents. While the DOORS tool can support other uses, the definition of DOORS requirements links can eliminate the problem that would arise by using the default DOORS links to connect requirements objects with other objects such as Test and Verification objects. While these objects can be linked to requirements objects, it is useful to be able to filter out these objects if one only wishes to see requirements objects that are linked with program-defined requirements links. The DOORS files that the GPS Wing and its vendors could share would use the structure shown in Figure 10:



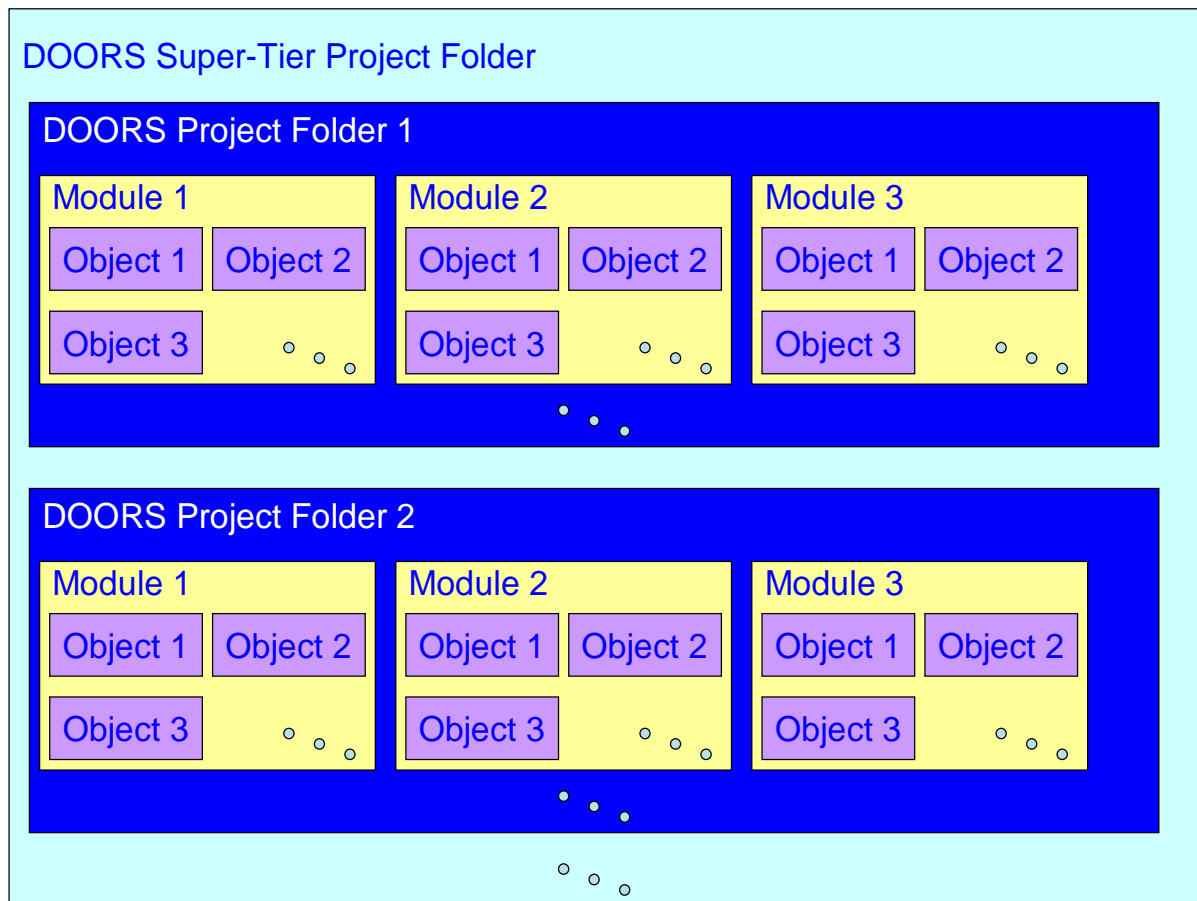


Figure 10. DOORS Database Structure

This structure applies to the document-centric structure in use as well as the requirements-centric structure that the GPS program could use. One advantage that is not implemented for the various GPS subsystem development programs is the linking feature that supports traceability. While the DOORS OI will mandate that programs not use the default DOORS links, this will not be an issue for most programs because they have not linked their requirements objects yet. There are links defined between the Block III Space and Control CDD and System Specification that reside in their own DOORS project folder. This project folder will eventually have objects that are linked to the separate DOORS project folders for the Block III Space Segment and Block III Control Segment programs

when those get underway. In general, programs that are represented by project folders in Figure 10 could link their requirements objects across modules and other project folders that reside in the same super-tier project folder.

## **1. Requirements Development**

AFSPC provided the GPS Wing the June 3, 2005 CDD instead of agreeing to provide requirements in a manner that supports a requirements-centric use of the DOORS database. In doing so, the customer made a decision that affects how other customers and stakeholders communicate their requirements and needs to the GPS Wing. The long-term impact will include a greater amount of work for all customers.

By employing a requirements-centric approach, the GPS program could have taken advantage of existing requirements in order to limit the amount of requirements development necessary for new deliverables. Rather than reinvent legacy requirements, the GPS Wing could reuse these legacy requirements and focus on developing new requirements only. As an example, consider the U.S. civil aviation community's interest in GPS service continuity. While also interested in new civil signals and the capabilities that would come along with them, this stakeholder group provided detailed backwards compatibility requirements through the IFOR to emphasize the civil priority for the GPS to continue providing existing services at equal or greater levels of service quality (Cryderman, J., personal communication, July 24, 2006). These levels of service quality are measured in such general terms as availability, integrity, and accuracy. These types of quality are enumeration choices for the *Performance Area* recommended attribute type in the draft DOORS OI (see Table 3). The development of these "backwards compatibility" requirements from this GPS stakeholder group would be much simpler and prone to fewer omissions and errors if the GPS program reused legacy requirements objects rather than rewrite legacy requirements into new capability or specification documents. This type of

approach would facilitate efficient documentation of requirements across generations by ensuring that legacy requirements that are still valid continue to drive development.

For a new subsystem development program, legacy requirements could be assigned a newly defined effectivity attribute choice among the already existing enumeration choices. The new effectivity attribute for legacy requirements would link these requirements to new subsystem development programs. Figure 11 shows a notional example of this requirements reuse practice by including two Block IIF Control Segment requirements among the Block III Control Segment requirements. The current document-centric practice would have many requirements objects duplicated unnecessarily in different DOORS projects folders within a super-tier project instead of limiting new requirements objects to those for new requirements only. For this suggestion to work, legacy requirements would need to be stored in a format that makes them reusable. In other words, the program would need to define and use effectivity attributes for the legacy requirements that are stored as DOORS objects—something not done for most DOORS objects in the GPS program.

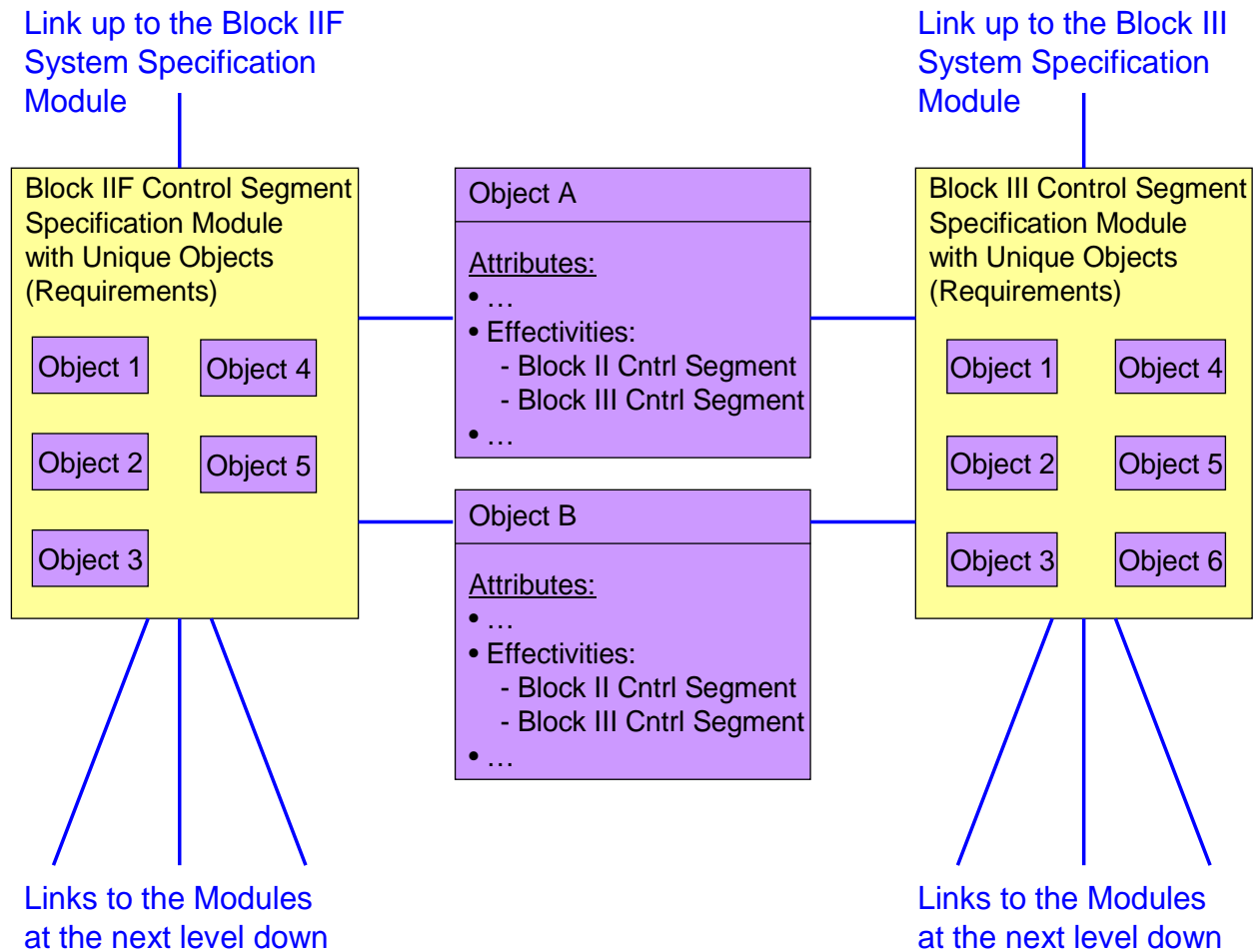


Figure 11. Example of Existing Requirement Reuse in the next Block Upgrade

Beyond GPS, this cross-generation benefit would apply not only to legacy systems that are continuously upgraded, but also to development efforts for new system requirements when the new system will replace the old system completely. In the DoD acquisition structure and while using a requirements-centric approach, it could be possible to export requirements database information from one program office (or Wing) to the database of another. The requirements will change, but the objects could be rewritten while preserving the types of requirements the new program office must address. However, the new program's decision makers would need to weigh the costs versus benefits to overcoming technical challenges if it becomes necessary to transfer the

information from one requirements management database to a dissimilar tool. If customers like Air Combat Command and Air Force Space Command provided tool-specific requirements-centric inputs and enforced the use of that single tool by its acquisition Wings, then tool incompatibility would not be a big issue.

## **2. Requirements Management and Documentation**

Requirements management deals with the decisions regarding requirements changes. Requirements documentation deals with how requirements are stored, handled, and presented in reports. Effective documentation of baselined requirements helps decision makers access the requirements information they need in order to support efforts to change requirements. Requirements documentation also addresses linking requirements to organize them better and support analyses, tracking changing requirements attributes, and generating formal reports. The goal for performing these requirements management and documentation functions well is to improve the speed, quality, and confidence of engineering and program management decisions.

Because the GPS program works with vendors that also use DOORS, one of the most important requirements documentation and management issues involves the transfer of requirements information between the GPS Wing and its vendors. Currently, this transfer occurs with the exchange of requirements documents. The government provides high-level requirements documents that are compliance documents on a contract, and the vendors share the lower-level specifications they produce in order to satisfy these higher-level requirements. The GPS Wing technical experts, who consist primarily of FFRDC personnel and SETA contractors, review the vendor-produced documentation in order to ensure that the requirements contained within these documents are complete and accurate enough to address requirements in higher-level specifications. Linking and reviewing a hierarchy of requirements stored in DOORS could accomplish the same goal more efficiently and with greater assurance. Instead of

transferring documents, vendors could provide their DOORS objects, modules or project folders for lower-level requirements instead. Vendors have already exchanged DOORS extracts with the GPS Wing, but neither party relies on this method for the purpose of exchanging requirements information that will undergo review.

Creating a hierarchy of requirements in DOORS with clear parent-child relationships would ultimately support efforts to verify that a produced subsystem satisfies its requirements. This requirements development method would result in a database for managing requirements and eventually supporting design verification activities. The GPS Wing would be the only organization with copies of all DOORS project folders within its super-tier project folder. As indicated in Figure 12, the GPS Wing would exchange copies of DOORS project folders with the appropriate vendors. Doing so ensures a common baseline understanding of each program's requirements between the GPS Wing and the appropriate vendors. Vendors would begin by using their copies of the government-created DOORS database information to grow requirements trees to greater depths. Within the project folders shown in Figure 12, changes to the modules for the government-defined system and segment specifications would require government coordination.

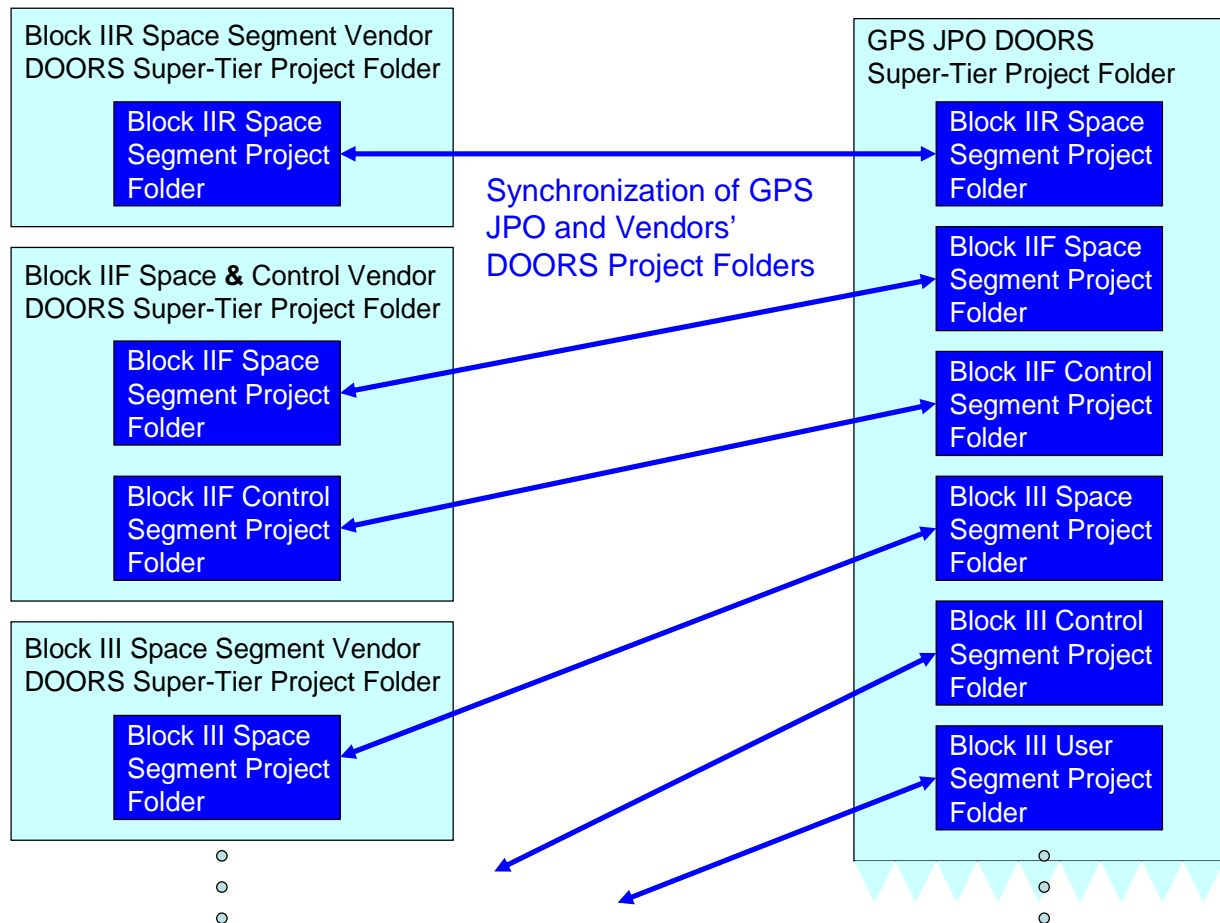


Figure 12. Synchronizing GPS Wing and Vendors' DOORS Information

If there is a change in practice to a requirements-centric approach for the GPS program, some stakeholders will still prefer to have access to document-style descriptions of requirements. For these people, the DOORS database can support the production of reports that emulate this style, and these stakeholders could produce reports themselves by establishing accounts and learning how to use the tool. However, much of the background information found in many such documents would have to come from sources other than the requirements objects. This information could reside in non-requirements objects in DOORS or in documents that exist to preserve background information.

The system Configuration Control Board (CCB) personnel in the Systems Engineering Division's Requirements Branch have both read and write access, but most requirements stakeholders should have read-only access to the GPS DOORS database. Organization of GPS program requirements in a requirements-centric fashion and granting broad read-only access would benefit engineers by allowing them to study requirements in a format that supports their requirements organization and traceability needs best, and support other stakeholders without causing a significant long-term inconvenience. The short-term inconveniences would include establishing accounts and receiving the training necessary to navigate the database, trace requirements, and produce reports. Requirements stakeholders should develop a familiarity with DOORS that matches the familiarity that many have with word processing and electronic mail applications. If the goal is to improve the management of GPS requirements, then the solution will also need to include the enforcement of consistent practices that support this goal.

**a. *Requirements Defined, But Not Needed***

Current requirements are not the only ones worth managing. It would be useful to track requirements that no longer apply to any development program because they have been satisfied or because of a reduction in technical scope for existing programs. The draft DOORS OI identifies the 'Was' *Requirement* attribute as a way to track these requirements. If the requirement becomes valid again as a result of new activities for a new program, a program manager or systems engineer could recommend the assignment of the new effectivity attribute that indicates the new program to which the 'Was' *Requirement* should belong.

There are other possible 'Was' *Requirements* that may never become requirements for the GPS Wing and its vendors to satisfy. Even so, it is still useful from a requirements management perspective to retain these requirements in the database for reference purposes. Someone involved in the



GPS program may not know that a requirement is no longer valid or understand why. Requirement history is important for understanding why some requirements fade and others remain valid from one generation to the next. This understanding reduces the amount of time wasted when reevaluating a requirement.

***b. Requirements Needed, But Not Defined***

There are cases when requirements development activities for a capability do not account for all requirements that need to be satisfied in order to fully implement the capability.

For example, the GPS Wing Space Segment Group has already supported the production and launch of Block IIR satellites that can broadcast the M-Code ranging signal. However, because of a reduction in the scope of the Control Segment's Block IIF contract, the Control Segment Group does not have a requirement for monitoring such a signal or for providing an appropriate Navigation message to combine with it. This example shows how requirements development is complete for one segment, but not for the entire system.

As a practice to be added to the GPS Requirements OI, the GPS Wing should specify the development and management of system-level and **all** segment-level requirements necessary to implement a capability. The M-Code monitoring capability is now planned for the first increment of the Block III Control Segment.

A special case of undocumented GPS Control Segment requirements could have been solved easily by using DOORS with a requirements-centric approach. The Control Segment's offline tools were developed without GPS Wing support in order to support the existing needs of the Control Segment operators. Before the GPS III Space and Control CDD documented these requirements, engineers could have created a separate

module for these requirements objects and linked them as needed without having a requirements document to rely on.

**c. *Supporting Analyses for Baseline Changes***

After requirements definition and baseline approval, analysis activities continue throughout the system's lifecycle. A requirements-centric approach to requirements management and documentation would support these analysis activities. In a manner similar to other program organizations, the GPS Wing may decide or be required to conduct *What-If* drills to determine the effects of possible changes to requirements. The drills may result from internal questions that arise due to technical development challenges, disputes between vendors developing opposing sides of subsystems that will share an interface, or because a customer like HQ USAF would like to study alternative requirements. During these drills, the subject matter experts conduct the technical analysis necessary to assess the impacts of requirements changes on subsystem programs. Currently, these individuals rely solely on their expertise and diligence because they do not have a requirements-centric implementation of DOORS to support their analysis. The DOORS standard view offers a sequential list of a module's objects—headings, paragraphs, tables, and figures extracted from each requirements document in the order that they appear in a document. A traceability view would show how child objects are linked to parent objects. In short, additional analysis develops requirements further. The ability to trace up or assess impacts down a properly linked requirements hierarchy would support these efforts. However, there are no links established to support requirements traceability analyses.

The GPS Wing would benefit from DOORS use practices that support rapid identification of all related requirements and allow users to then proceed with their analysis. A requirements-centric approach in which hierarchies of requirements are linked properly would improve analysts' and decision makers' collective confidence that the conclusions take into account all

relevant requirements. The customer would benefit by receiving rapid and well-researched answers with which to make decisions about changing requirements. In addition to technical confidence, program decision makers and customers would also benefit from the stronger confidence in cost and schedule analyses that accompany technical analyses. These decisions are made using the system Configuration Control Board (CCB) process that impact the working groups and organizations named in Figures 6 and 7. Organizations include the appropriate vendors as well as the various GPS Wing organizations such as the Systems Engineering Division, affected Program Managers' Groups, the Program Control Division, and the Contracts Division. Working groups that provide recommendations to the CCB include the GPS Wing Engineering Review Board (ERB) and Interface Control Working Groups (ICWGs). Changes approved via this CCB process require subsequent updates to relevant documentation and DOORS objects that mirror this documentation.

### **3. Requirements Validation, Verification and Testing**

Requirements validation and verification are other forms of analysis that would benefit from a requirements-centric approach to requirements engineering. If successful, validation and verification events bring closure to open requirements. Clear traceability of lower-level requirements up to System-level requirements supports final validation, verification, and testing.

#### **a. Validation**

Customers with government DOORS accounts would have access to the information needed to validate system-level, segment-level or even lower-level requirements. Invalidating requirements derived from the CDD or system-level requirements will reveal misunderstandings about a customer's intent. If interested in greater levels of detail, customers would have an opportunity to see how their requirements develop and understand issues that arise. Access to DOORS should encourage customers to interact more with the GPS Wing to

resolve issues. Because customers often do not appreciate the challenges that their requirements can cause or the consequences of those challenges, customers may be willing to modify or relent on requirements that are not as important as once thought. As a result, this additional insight would offer opportunities for customers to contribute to solutions that save cost and schedule for more important capabilities.

***b. Verification***

Establishing and using a hierarchy with clear and accurate relationships would eliminate the ambiguity that exists presently and fuels conflicts between vendors and GPS Wing personnel during verification events. DOORS can support the development and management of requirements in this way to make requirement verification progress easier to assess.

For example: The Block IIF System Specification, Block IIF Space Segment Specification, and the Block IIF Control Segment Specification all have requirements traceability and verification matrices. In its matrix, the System Specification shows internal links among its paragraphs. In the Space and Control Segments' specifications, their matrices define links between their respective requirements and requirements in the System Specification. This type of traceability format is full of errors, cumbersome, and lacks depth beyond one level. A requirements-centric approach to using DOORS would offer the opportunity to provide greater accuracy and depths of requirements traceability in the GPS Wing database. While the authors of the GPS III Space and Control System Specification wrote that specification to address the CDD's requirements, not all requirements are linked correctly or unambiguously to parent requirements:

- some system specification requirements trace to CDD statements that are not requirements statements

- some system specification requirements trace to unrelated CDD requirements statements
- some system specification requirements trace to nothing in the CDD

(Campbell, J., personal communication, July 25, 2006)

These kinds of situations lead to difficulties in verifying requirements. By providing clear visibility into the relationships in a requirements hierarchy, a requirements-centric approach to requirements engineering would help the GPS Wing prevent such traceability and completeness problems from occurring. In the requirements-centric approach, child requirements derive directly from parent requirements, thereby eliminating the possibility that a lower-level document has parentless requirements (orphans). This approach would provide better visibility into whether a parent requirement has all of the child requirements that are needed to support eventual satisfaction of the parent requirement. The linkage of requirements in the DOORS project folders shared by the GPS Wing and the appropriate vendor share would support requirements traceability without the need to corroborate the requirements statements of multiple specifications.

### ***c. Testing***

A hierarchical structure of linked requirements implemented with a tool like DOORS can simplify verification planning and speed requirements verification itself. Test failures would be easier to track by using requirements attributes that address test status. These attributes could implement enumeration types such as *not tested*, *pass*, or *fail*. The default attribute could be *not tested* until the systems engineer conducts a sanctioned verification test. Sanctioning authority would depend on the level of requirement and stage of testing. For example, a system-level test would require GPS Wing authority to modify a requirement's attribute. As another example, a vendor would have

jurisdiction over subsystem component-level tests for which these kinds of lower-level requirements would exist initially within projects created in the vendor's DOORS project folder, and then be transferred to the GPS Wing for inclusion within its corresponding DOORS project folder.

### **C. REQUIREMENTS CONTROL**

Even if the GPS program adopts a requirements-centric approach for its requirements engineering activities, the benefits of this approach would be limited to some extent by the amount of control the GPS Wing exercises over requirements. Vendors exercise control over Segment specifications that, in some cases, have an effect on the work of other vendors that support other parts of the GPS program. Government control over the System-level and Segment-level specifications would help the GPS Wing in its role as the prime integrator of GPS subsystems. Ultimately, the GPS Wing is responsible for successful integration, and must demonstrate this success to its customers. Vendors should expect to support, but not lead the integration effort of the subsystems they deliver.

To ensure requirements discipline and facilitate systems integration, the GPS Wing should retain control over System-level and Segment-level requirements for the GPS III Space Segment and Control Segment contracts. The program learned through experience already that it is risky to allow a prime subsystem vendor to be the major subsystems integrator of deliverables for different Segments. Vendors seeking to pass verification events have two choices when their products fail to pass a test in the specified environment—they can either redesign a product so that it will pass, or the vendor can relax the requirements until a product passes its test. The latter option is often less desirable to the government because the government is stuck with the consequences. Vendors' customers (like the GPS Wing) will most likely prefer a choice over whether there will be a product redesign—which would add schedule and cost to a program—or whether it would prefer to relax the vendor's

requirements. Without understanding the impacts, the government is not likely to accept the relaxation of a requirement.

#### **D. THE DRAFT REQUIREMENTS OPERATING INSTRUCTION (OI) AND THE DOORS OI—EXPECTED IMPACTS AND RECOMMENDATIONS**

The GPS Wing's direction regarding requirements engineering activities will be captured by two operating instructions—the Requirements OI and the DOORS OI. The Systems Engineering Division would like both approved before the end of 2006. The Requirements OI will offer important advice about defining requirements effectively, which should make it an effective companion document for the DOORS OI. The DOORS OI will discuss links to support traceability, but the document-centric focus on the CDD and specifications make linking requirements more difficult. The DOORS OI would have a greater positive impact on the GPS program if it directs a requirement-centric approach to requirements engineering and directed the use of its listed attributes.

The Requirements OI's checklist for defining requirements will help program personnel to improve the statement of requirements. Shown already in Chapter 3, the checklist is as follows:

- Is it clear?
- Is it as short as it can be?
- Does it apply to a defined type of user?
- Does it have a reasonable priority?
- Is it verifiable?
- Is it a single requirement?
- Is its source shown?
- Does it have a unique identifier?

- Is it genuinely a user requirement, not a design constraint?

(Chief Engineer GPS Wing, 2006b draft)

This checklist of questions will help personnel make a determination about whether to restate a requirement or to eliminate it. Restating a requirement may actually require that the requirement statement be longer or be broken into distinct parts in order to capture its entire intent or satisfy multiple stakeholders throughout the GPS program. The goal should be to capture all the information that is necessary to design the system, include nothing more than what is necessary, and document this information in a way that prevents ambiguity.

Mandating the recommended attributes listed in the draft DOORS OI would help ensure consistent requirements documentation practices across the GPS program. Doing so would also help to satisfy the Draft Requirements OI checklist by ensuring answers to some of the checklist questions, such as those that address verification and priority. Of all the GPS subsystem development programs, the User Segment Group's Advanced Digital Antenna Panel (ADAP) DOORS project folder demonstrates the best example of using attributes among the GPS Segment's programs. Most other subsystem development programs use no attributes other than the attributes assigned automatically by DOORS. The reason why the nonuse of attributes is likely to continue stems from the document-centric approach to requirements management that allows program personnel to access requirements documents without accessing DOORS. Much of the information that would exist as requirements attributes does not exist in these requirements documents. Consequently, decision makers will not have convenient access to this information.

#### **E. THE USE OF THE WORD *SHALL* IN SPECIFICATIONS, INTERFACE CONTROL DOCUMENTS AND INTERFACE SPECIFICATIONS**

The statement of requirements in ICDs and ISs underscores a problem the GPS Wing faces with its vendors. ICDs should merely describe external and internal interfaces rather than also specify requirements. However, vendors



claim that without *shall* statements, certain activities are out of the scope of their contract. The use of '*shall*' statements in ICDs and ISs solves the government's problem of getting vendors to verify that the systems they deliver will interface properly with the other GPS subsystems. However, because the intent of interface documents is to describe rather than require, the GPS Wing will need to ensure that future contracts include requirements for verification of not only the vendor's deliverables, but also the proper interface of these deliverables with other GPS subsystems. In the absence of a shift away from specification documents, compliance documents such as system or segment specifications would be a more appropriate place to levy verification requirements for interfaces. In a requirements-centric model, verification requirements would need to exist at the segment or system level also.

Vendors have clear and particular definitions for the words like *shall*, *must*, and *will*. If the vendors agree to include ICDs, ISs, and specifications as compliance documents on their contracts, then these documents shall include the word *shall* to help designate vendors' requirements. The remaining risk with respect to the use of this word is that the government has not issued a current and precise definition of *shall* or any other such words to be agreed upon by all vendors. (The government rescinded MIL-STD-961, which defined *shall*, *will*, and *should*.) Instead, it is the vendor who defines the meaning of these as well as other terms, such as *must*, that may not have military-wide or even GPS program-wide accepted meanings. For a program in which there are different vendors responsible for developing and producing different subsystems, any inconsistencies in vendors' use and interpretations of these kinds of terms increase the risk of incompatibilities due to unsatisfied requirements. In addition to technical issues, differences in interpretation over whether a statement is a requirement or not can also lead to contractual difficulties that delay the pursuit of a necessary technical solution.

The government should redefine the definition of *shall* and any other words it intends for use in defining the contractual obligations of the government

and its vendors. After doing so, the government should also ensure proper and consistent use of these terms in its capabilities documents and specifications. The GPS program has a Block III CDD for the Space and Control Segments that uses statements with words other than *shall* that appear to be requirements statements. For example, the word *should* appears throughout the CDD—including several instances in Section 6: System Capabilities Required for the Current Increment. MIL-STD-961 stated that the word *should* relates to a goal. However, there is no current government-approved definition for *should* that applies to military acquisition programs, and this word is not defined in the CDD either.

## **F. CHAPTER SUMMARY**

This chapter offers suggestions for improving the GPS program's requirements engineering and system integration effectiveness by standardizing on technology already available to the program. Currently, the GPS program is not practicing an effective way to develop, manage, verify requirements; or include consistent practices across subsystem acquisition programs. Although the GPS program and its vendors have a tool capable of supporting a requirements-centric approach, they are not using the DOORS tool to do so. However, the program has taken steps in 2006 to improve its requirements engineering activities by writing operating instructions that provide direction to program personnel; but there are still opportunities to improve the draft DOORS OI. The draft Requirements OI will eventually close a gap in program direction regarding requirements engineering. While this chapter recommends abandoning a document-centric approach in favor of a requirements-centric approach, current realities that face the program will likely divert decision-makers' collective attention towards overcoming higher priority financial, schedule, and technical challenges.

## **V. CONCLUSIONS**

### **A. INTRODUCTION**

This research proposes ways to improve the requirements engineering work at the Air Force's GPS Wing, the acquisition program office for this civil-military system. The ultimate benefit is faster and better-informed decisions made by GPS program leaders who must balance the needs of multiple stakeholders. These stakeholders rely on this system for positioning, velocity, and timing services. While decisions ultimately depend on human interaction and persuasion, organizing the requirements information effectively can lead to a better decision-making process. When relevant information is available in a useful standard format, people make more informed, rational and confident decisions.

For the GPS Wing to be effective, all three segments—Space, Control, and User—must work together. As a result, the GPS Wing must ensure proper allocation of requirements across these segments and integrate the subsystem acquisition program deliverables from these segments. The Wing should consider its investment of time, training, and funds carefully when evaluating requirements methodologies that support integration efforts. The GPS Wing and its vendors use the same DOORS database tool and have experimented with exchanging DOORS files. By changing its model and processes to take advantage of the features offered by DOORS, the Wing can achieve more efficient integration.

### **B. CURRENT PROGRAM REALITIES**

While the program managers and engineers of GPS Wing recognize the need to improve requirements engineering practices, current realities facing the program pose challenges to doing so. The program has seen different rates of progress on all three Segment modernization efforts because of technical, schedule, and cost constraints. While the program must deliver on its technical

obligations and overcome its schedule delays, the current resource-constrained defense acquisition environment adds another obstacle to meeting the emerging needs of civil and military users. Customers like HQ USAF have even asked the GPS Wing to compress future capability deliveries while the GPS Wing faces repeated reductions in its technical staff. The GPS and other development programs operate under a schedule-driven environment in which the Control Segment Group is attempting to meet a December 2006 target for releasing its already-delayed Request for Proposal (RFP) for the Block III Control Segment contract. By having a schedule-driven RFP rather than an event-driven one, the GPS Wing faces an increased risk that it will miss requirements.

The GPS Wing has recognized that it should improve its requirements engineering practices by drafting the Requirements and DOORS Operating Instructions (OIs). These are unprecedented documents that will standardize requirements engineering across the Wing for the first time. The completed draft DOORS OI has room for improvement, and the enforcement of this OI for older programs may have costs that do not outweigh the benefits. Long term benefits are possible when using a requirements-centric approach that emphasizes reusing existing requirements objects. Creating new requirements objects to replace legacy objects would also make requirements development easier. When completed and approved, the Requirements OI should provide the guidance that is necessary to promote a consistently high level of quality for requirements across Segment development programs.

### **C. KEY POINTS AND RECOMMENDATIONS**

This research paper discusses all three facets to a requirements engineering methodology: models, tools, and techniques.

First, a requirements-centric approach or model would benefit the GPS Wing's requirements development, management and verification efforts. However, this kind of approach would require changes to the other two facets of the methodology: tools and techniques.

Second, the Wing can strengthen its requirements engineering efforts by taking advantage of underutilized DOORS features such as attribute definition and linking to support requirements traceability.

Third, the GPS Wing has begun to define techniques for the first time in the draft Requirements and DOORS Operating Instructions. Implementation and enforcement of these OIs will help improve the requirements quality.

Even with a shift in its requirements engineering methodology, there are other ways that the GPS Wing could improve the way it handles its requirements. The GPS Wing would also serve its customers better by insisting to its vendors that the GPS Wing control the top-level requirements baselines and interface definitions.

For example: The GPS Wing learned from its experiences with the Block IIR Space contract and the Block IIF Space and Control contract that government loss of control over the technical baselines for subsystem deliverables causes contractual and integration difficulties. These difficulties increase costs and delay schedules.

As the system integrator, the GPS Wing could reduce integration costs and ensure that subsystem deliverables work together properly. When vendors seek a change to requirements or interfaces that the government controls, the government can then lead the decision-making process to decide how it would prefer to handle the proposed change. The current situation is untenable where the GPS Wing finds itself forced to help one vendor adapt to changes made by another vendor.

In its contracts with vendors, the GPS Wing should also provide a single set of definitions for key terms that help to define the roles and obligations of the GPS Wing, other government entities, and all vendors who develop and produce GPS subsystem deliverables. Disputes and questions over contractual agreements cost the GPS Wing precious funds and development time. If the

GPS Wing defined these key terms, vendors would not need to specify definitions for these terms that may vary from one vendor to another.

Over the last decade, the GPS Wing has learned from its contractual experiences that it must do a better job of specifying clear and complete requirements to vendors in order to ensure that subsystem deliverables are operationally suitable.

One example of inadequate requirements specification involves the lack of vendor support for the transition to operations of the Block IIF Control Segment software and hardware deliverables. Another example comes from the vendor belief that 'shall' statements in ICDs and ISs are necessary to ensure that vendors verify the performance of interfaces between their deliverables and other GPS subsystems.

The government needs to ensure that it specifies a complete set of requirements that cover all system acquisition needs. Unfortunately, bad program experiences are the motivation behind the draft Requirements OI to improve and standardize GPS Wing requirements engineering practices.

#### **D. AREAS FOR CONDUCTING FURTHER RESEARCH**

Even if the GPS Wing were already following the recommendations of this research paper, there would still be other areas to search for improvements to the GPS program's requirements engineering methodology. Rather than making the best use of available resources such as the DOORS tool, research could focus on evaluating the combination of tools and techniques that would support the GPS programs interests best.

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